PRESENT AND PROSPECTIVE TECHNOLOGY FOR PREDICTING SEDIMENT YIELDS AND SOURCES

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PRESENT AND PROSPECTIVE TECHNOLOGY FOR PREDICTING SEDIMENT YIELDS AND SOURCES

Proceedings of the
Sediment-Yield Workshop,
USDA Sedimentation Laboratory,
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ABBREVIATIONS USED IN TEXT

bu, bushel
cm, centimeter
d, day
ft, foot
ft^2, square foot
ft^3, cubic foot
h, hour
hp, horsepower
lb, pound
lin ft, linear foot
m, meter
mi, mile
mi^2, square mile
mi^3, cubic mile
min, minute
mm, millimeter
pct, percent
p/m, part per million
s, second
V, volt
wk, week
yd, yard
yd^2, square yard
yd^3, cubic yard
yr, year

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FOREWORD

This publication contains papers presented at the Sediment-Yield Workshop sponsored by the USDA Sedimentation Laboratory, Oxford, Miss., on November 28–30, 1972. The meeting was originally planned as a workshop between Agricultural Research Service and Soil Conservation Service personnel. However, because of an intense show of interest the meeting was broadened to include representatives of other Federal agencies, State groups, universities, and consulting firms. About 150 participants—soil scientists, engineers, geologists, and sediment chemists—attended.

It was hoped that a free exchange of information on sediment yields and sources would avoid duplicated research and result in better coordination of programs and efforts in the field of sedimentation. The background, history, and importance of the subject were discussed. From this conference a new level of refinement was demanded in estimating sediment yields, especially in relation to sources and physical and chemical properties of sediments, and in selecting cost-effective measures for sediment control.

This proceedings, which includes 31 papers, presents material on the procedures presently in use to estimate sediment yield. Research in the area of yield and source predictions are summarized in a number of papers. The development of modeling techniques and concepts for sediment-yield predictions are explored. A number of different, but related, ideas on modeling concepts are presented in a state-of-the-art review.

From a review of the papers, it is obvious that there is a considerable amount of knowledge available in the field of sediment yield and sources. However, a new level of sophistication is needed, particularly because of the water-quality implications of transported and deposited sediments. The papers indicate many new avenues for needed additional research.

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EVOLVING EMPHASES IN SEDIMENT-YIELD PREDICTIONS

By Louis M. Glymph[1]

For purposes of this discussion, I would like to define sediment yield as the effluent from a soil-processing system. The system is a diffuse natural process, which we know as soil erosion. The system is distributed in time and space and can be accelerated or decelerated by a multitude of factors, including the activities of man. The system ranges from small to large, depending upon natural or man-induced constraints. The effluent from this soil-processing system is a heterogeneous mixture of mineral and organic matter in particle sizes ranging from small to large, with a variety of natural or acquired chemical properties. The effluent is transported and delivered from the system by flowing water.

In the United States we have been concerned about sediment yield to stream channels and reservoirs for about 100 years. In 1872 the city of Baltimore, Md., was dredging sediment from its water-supply reservoir, Lake Roland. Only recently, however, have we begun to appreciate the water quality implications of sediment and to see sediment as a pollutant in the same context as industrial wastes, effluents from sewage treatment plants, and other point sources of pollution entering our streams and water bodies. Seeing sediment in this new light requires a new level of sophistication in our technology for estimating sediment yields and for selecting cost-effective measures for sediment control or management in the interest of attaining water quality goals. Indeed, from the development thus far in the 1970's, there is an urgency in our need to know more about sediment yields and properties in relation to sources and how to control or regulate the supply.

Following in the wake of the Water Quality Act of 1965, States are passing laws that make it a criminal act to allow sediment to enter streams. Under the Iowa law,[2] State conservation districts can require landowners to use soil and water conservation practices for sediment control if cost sharing for new practices is available from Federal or other public agencies.

On September 21, 1972, Pennsylvania adopted regulations designed to prevent any increase in the naturally occuring sediment in streams.[3] The regulations set forth the conditions under which persons engaged in earthmoving activities are required to design, implement, and maintain erosion and sediment control measures under a permit system for surveillance and enforcement. The regulations require the development of an erosion and sediment control plan which shall (p. 3) "consider all factors which contribute to erosion and sedimentation including, but not limited to, the following: (1) the topographic features of the project area; (2) the types, depth, slope, and areal extent of the soils; (3) the proposed alteration to the area; (4) the amount of runoff from the project area and the upstream watershed area; (5) the staging of earthmoving activities; (6) temporary control measures and facilities for use during earthmoving; (7) permanent control measures and facilities for long-term protection; and (8) a maintenance program for the control facilities including disposal of materials removed from the control facilities or project area."

The Third Annual Report of the Council on Environmental Quality[4] warns of the need to place much greater emphasis on control of non-

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[1] Staff scientist, Erosion and Sedimentation Research, National Program Staff, Agricultural Research Service, U.S. Department of Agriculture (retired).

[2] Iowa General Assembly. 1971. An act relating to conservation of soil and water resources of the State, and to control of water pollution. House File 73, 64th Iowa General Assembly, 50 pp.

[3] Commonwealth of Pennsylvania, Environmental Quality Board. 1972. Implementation and regulations dealing with erosion and sedimentation control, 7 pp.

[4] Council on Environmental Quality. 1972. Environmental quality, the third annual report of the Council on Environmental Quality. Government Printing Office, Washington, D.C., 450 pp.

point sources of pollution if our enforcement programs and financial investments for water quality are to have the maximum effect. The report states (p. 16) "that even if all discharges of municipal and industrial pollution were stopped, many streams would still be polluted as a result of discharges from runoff sources."

The Federal Water Pollution Control Act Amendments of 1972 (Public Law 92–500) devotes much atention to the control of pollution sources through development and implementation of areawide waste-treatment plans, including control of runoff from fields and crop and forest lands, mining activities, and construction activities.

Undoubtedly, our understanding of erosion and sedimentation processes has expanded considerably since the dredging of Lake Roland in 1872. We have learned that it is generally more reasonable to keep sediment out of streams than to remove it once it gets there. Nowadays we are inclined toward erosion control and other preventive measures as an alternative to dredging of sediment when it bulks in quantities of damaging proportions some place downstream.

We are now being called on to adopt the philosophy of "control at the source" as our approach to control of water pollution by sediment. This attitude about sediment is thoroughly consistent with that applied to effluents from industrial and manufacturing processes, municipal sewage treatment plants, etc. The Federal Water Pollution Control Act Amendments of 1972 includes sediment along with other pollutants when it states that "it is the national goal that the discharge of pollutants into the navigable waters be eliminated by 1985."

SEDIMENT AS A POLLUTANT

Sediment is the product of a selective process in which the finer and lighter particles are preferentially removed and carried away by runoff and streamflow. Sediments, therefore, are generally higher in clay, silt, and organic matter than the soils from which they are derived. These particles and organic compounds have great capacity for absorption of pathogens, viruses, plant nutrients, pesticides, and other chemicals. Thus, the commitment for identification and control of pollutants from runoff sources requires improved understanding of the physical and chemical properties of sediment in respect to specific erosion sites. We can no longer be satisfied with knowing the volume of sediment involved; for many cases we now must also know about the properties of the constituent sediments in relation to their source.

For instance, persistent chlorinated hydrocarbons such as dieldrin, which is used extensively for control of corn root webworm (*Crambus coliginosellus* Clemens), have low solubility in water but are strongly absorbed by soil particles. Consequently, such pesticides do not move downward through the soil with infiltrating waters, but they can move into streams and other water bodies in significant amounts attached to sediments if erosion occurs.

Phosphorus applied as a fertilizer is also strongly adsorbed onto soil particles and moves to streams and other water bodies primarily attached to sediment from soil erosion. Studies are showing that even nitrogenous fertilizers, which are highly soluble in water, also leave land surfaces adsorbed on sediment in much greater proportions than suspected.

Significant nitrogen-sediment relationships are illustrated by an Agricultural Research Service study of nitrogen discharge in surface runoff from agricultural watersheds in southwestern Iowa.[5] Included in this study are two watersheds in corn planted on the contour, one fertilized each year with nitrogen at the recommended rate of 150 lb N/acre and the other at 400 lb N/acre. For the 3-yr period 1969–71, inclusive, the watershed with the high fertility treatment discharged 2.7 lb N/acre dispersed in the surface runoff and 32.6 lb N/acre adsorbed on the sediments. For the same period the watershed with the recommended level of fertilization discharged 1.7 lb N/acre dispersed in the surface runoff and 20.6 lb N/acre adsorbed on the sediment. Thus, 92 pct of the nitrogen discharged from these watersheds was carried by the sediment. In the same experiment, sediment N losses were 86 pct of the total N losses from a level-terraced watershed in corn and 51 pct of the total from a bromegrass pasture watershed.

[5] Schuman, G. E., Burwell, R. E., Piest, R. F., and Spomer, R. G. 1973. Nitrogen losses in surface runoff from agricultural watersheds on Missouri Valley loess. Journal of Environmental Quality 2(2): 299–302.

We are also finding that sediment sometimes serves as an effective scavenger in removing chemicals from the surrounding waters. A potential beneficial role for sediment in removing phosphorus discharged into streams with sewage effluent is indicated by findings at the USDA Sedimentation Laboratory, Oxford, Miss. A sediment concentration of 10,000 p/m of Memphis soil, for instance, has the adsorption capacity to reduce the phosphorus concentration in sewage effluent from the average of 6.6 p/m to 4.3 p/m. Most soils in the Southeastern States and in many other parts of the country have a high capacity for fixing phosphorus. Thus, there are circumstances where phosphorus-deficient sediments from farmlands are capable of effectively reducing the amount of phosphorus dissolved in industrial and municipal waste waters that flow through agricultural watersheds.

PREDICTING SEDIMENT SOURCES AND YIELDS

If one wants to eliminate or reduce the supply of a pollutant, he first needs to know where the pollutant originates. And after doing something to diminish the supply, he wants to know how effective his actions have been and whether he needs to do some more of the same or evolve some new routines for use in management or control of the processing system.

We have a substantial body of information for all parts of the country about the amount of sediment expected to arrive at downstream points over the long term. We are not nearly as well prepared, however, to speculate quantitatively as to where the sediment comes from or to specify what erosion sites supply what sediment reaching downstream points. It follows, then, that we are not nearly as well prepared as needed for making definitive statements about the impacts of our program measures upon sediment yield. We are better able to design and install measures for reducing erosion rates or trapping sediments than we are for specifying the downstream destinations of the residual sediments or new sediments entrained because of program measures installed upstream.

In the main, we predict sediment yield by using one or more of four methods or approaches:

1. *The sediment-rating curve-flow duration method* requires concurrent field measurement of streamflow and sediment to establish an average relationship between parameters of streamflow and sediment quantity. The method is often used for establishing the amount of sediment expected to reach large reservoirs or other points on principal tributaries and main rivers. The method, however, is generally not applicable in estimating sediment yields at problem sites in upstream watersheds because of the difficulty and expense of obtaining the required data for the large number of sites potentially of concern. Problems are also encountered in using the sediment-rating curve-flow duration method for estimating the effects of program measures upon sediment yield because of imponderables and uncertainties in arriving at a sediment-rating curve for conditions with the program in effect.

2. *The reservoir sediment-deposition survey method* involves measurements by field survey of the volume of sediment accumulated in a pond or reservoir. The measured volumes are converted into weights, adjusted for reservoir trap efficiency, and expressed as rates of accumulation according to the age of the reservoir or the time interval between surveys. Deposition surveys on a number of reservoirs in a land resource area, watershed, or river basin are often compiled and summarized to show relationships between sediment yields and size of drainage area. This approach gives useful general information of the magnitude and variation of sediment yield in the region of interest, but has limited value for forecasting sediment yield from an individual watershed where no measurements have been obtained. The method also has limitations in estimating the effects of program measures on sediment yield.

3. *The sediment-delivery ratio method* requires a factor expressing the percentage relationship between sediment yield from a watershed and gross erosion in the watershed in the same time period. Sediment-delivery ratios are developed from the sediment yields obtained by reservoir surveys or measurements at suspended-load stations in comparison with erosion in the watershed. The erosion quantities for sloping uplands are computed by erosion prediction equations and are estimated by various procedures for gullies, stream channels, and other sources. In op-

erational programs, derived quantities of watershed. The erosion quantities for sloping uplands sediment-delivery ratio to give estimates of sediment yield. Since the method deals with calculated and estimated quantities of erosion on the watershed with and without treatments, it has a rationale for estimating program effects upon sediment yield, under the assumption that the same sediment-delivery ratio applies for both the "before" and "after" conditions. Sediment-delivery ratios have been developed for much of the eastern half of the United States, but scanty rainfall data and other complicating factors have precluded use of the method in the West.

4. *The bedload function methods* make use of mathematical equations developed for calculating the rate and quantity of movement of materials constituting the bed of alluvial channels. Application of these equations requires information on sediment particle sizes, channel gradients and cross sections, and a flow-duration curve. The equations often give widely different results for the same conditions.

In each of the methods, the watershed is treated as a lumped system. They deal with the watershed as a whole, rather than with its constituent features, in deriving the quantity of sediment expected at a point on the watershed. Though in the sediment-delivery ratio method erosion rates are calculated separately for significant sites, they are then aggregated and the total compared with a measured sediment amount for the watershed as a whole. In effect, therefore, this method also treats the watershed as a lumped system.

Greater specificity regarding the sources and properties of sediments and the effectiveness of measures for stabilizing sediment sources requires that our technology treat the watershed as a distributed system. For dealing successfully with water pollution associated with runoff from nonpoint sources, we need technology for sediment-yield predictions that begins with the erosion process and objectively and specifically accounts for disposition of the eroded material as it moves downstream from the point of origin.

Since water is the initiating force in the soil-processing system and also the transporting agent for the effluent, it seems logical that sediment-yield prediction also needs to be integrated with hydrologic and sediment-transport phenomena. Hydrologists are developing mathematical models for predicting hydrographs of runoff and streamflow as cumulations routed from the significant soil-cover-treatment complexes in the contributing watershed. We need to know how to route sediment along with the water from these same soil-cover-treatment complexes and to be able to cumulate hydrographs of sediment discharge at downstream points in which the amounts, particle sizes, and physical and chemical properties of the sediment are specified in relation to the erosion sites from which the sediment is derived. We have already learned that sediment comes from many different erosion sites including farm, forest, range, and urban land surfaces, gullies, streambeds and streambanks, roads and highways, construction sites, mining operations, etc. Developing a prediction procedure to account for the sediment from its multiplicity of sources will not be an easy task.

THE CHALLENGE

I have emphasized the water quality implications of sediment-yield predictions. Of course, we will continue to need information on sediment yield and sources for other purposes. Sediment continues to affect the useful life of reservoirs, water treatment for municipal and industrial uses, cleanup following floods, fish and wildlife habitats, water-based recreational opportunities, urban developments, watershed protection, and still other considerations calling for forecasts of sediment yields and the prescription of methods and programs for ameliorating or reducing the sediment problems. But in addition to our traditional concerns about sediment yields and sources, I think we should anticipate the imminence of our being caught up in the requirement that sediment, the effluent from the processing system known as soil erosion, will have to meet prescribed standards of volume and constituent properties. This is bound to make our job more difficult and more interesting.

PROCEDURES USED IN THE SOIL CONSERVATION SERVICE TO ESTIMATE SEDIMENT YIELD

By John N. Holeman[1]

The Soil Conservation Service (SCS) estimates sediment yield for a wide variety of purposes. SCS programs (conservation operations, river basin studies, watershed planning and flood prevention, Great Plains conservation, and resource conservation and development), which involve the use and protection of land and water resources, require information on amounts of sediment to expect from specific areas.

A fundamental part of these programs is land treatment. Conservation measures and practices include terracing of sloping cropland, critical area planting, contour farming, stripcropping, land leveling, and minimal tillage. Proper land treatment helps keep soil in place and is the most economical method of reducing sediment yield.

Structural improvements such as earth dams that trap sediment and reduce sediment yields downstream, are also important to SCS programs. A pressing SCS concern is predicting the amount of sediment that will reach and be deposited in reservoirs. Storage space for sediment must be allocated in the capacity planned for reservoirs so that the space for beneficial use will not be encroached on during the design life of the structure (fig. 1).

Accuracy in predicting the space needed for sediment storage is important since overestimating the sediment yield adds unnecessarily to the cost of the structure, and, on the other hand, underestimating the sediment yield shortens the useful life of the structure and the services associated with it.

In SCS geologists are responsible for predicting sediment yields from areas ranging from small watersheds to large river basins. They base their predictions on the basic data available, interpreted according to the principles of sedimentation. The accuracy of the predictions varies with the basic data available; knowledge of the processes of erosion, entrainment, transportation, and deposition of sediment; and the predictability of changes in the watershed that will alter sediment yield.

The four basic procedures used in SCS to estimate average annual sediment yield depending on the environment and data available are (1) gross-erosion and sediment-delivery ratio determinations, (2) predictive equations, (3) suspended-sediment load measurements, and (4) sediment accumulation measurements. It is desirable to use more than one method for verification, if possible.

1. The gross-erosion and sediment-delivery ratio procedure has been used extensively and successfully for many years by SCS, especially in humid areas of the United States. It is well suited for estimating current sediment yields and predicting the effect of land treatment and other measures on future sediment yields. The gross, or total, amount of erosion in a drainage area is the summation of all the erosion occurring. It includes sheet and rill erosion and channel erosion (gullies, channel degradation, streambank erosion, etc.). The methods of determining the

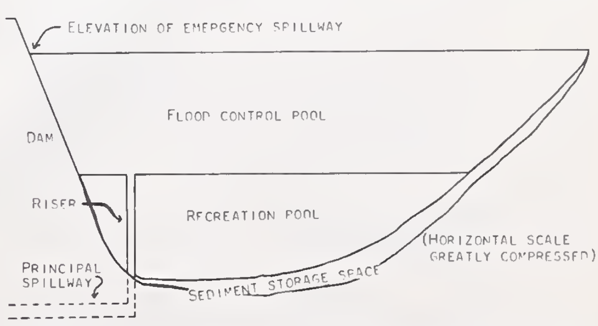

FIGURE 1.—Example of an SCS-designed multipurpose reservoir.

[1] Geologist, Engineering Division, Soil Conservation Service, U.S. Department of Agriculture, Washington, D.C. 20250.

amount of each type of erosion are presented in more detail by Renfro and Hunt in this proceedings. Sediment-delivery ratios vary with a number of factors, such as sediment source, including magnitude and proximity to streamflow; the transport system; the size of the eroded material; and watershed parameters ranging from the drainage area and the shape of the land surface and the basin to the relief-length ratio. Renfro discusses this in more detail. The sum of all erosion multiplied by the appropriate sediment-delivery ratio gives sediment yield, using this procedure. The form shown in figure 2 is convenient for summarizing sediment yields, predicting sediment deposition, and estimating sediment storage requirements for reservoirs.

2. Predictive equations based on watershed parameters have been developed in some areas to arrive at sediment yields directly. These equations express sediment yield as a function of several measurable, independent variables. Some of the variables are drainage area, annual runoff, rainfall, temperature, pH of soils, relief-length ratio or average slope, particle size of the surface soil, and others. Tested predictive equations are not numerous, but when they are available, they are used in SCS with the restriction that their application is confined to the specific areas for which they were developed. Flaxman[2] discusses some of the factors that he has found to be important in the West and some relationships he has developed for predicting sediment yield.

3. Suspended-sediment load records are available on a few streams of such size as to be of concern to SCS. In the absence of records, SCS may initiate a sampling program. Water discharge can be measured by gaging at particular stream cross sections. Sediment yields can be estimated from a period of these measurements. The average sediment concentration is multiplied by the volume of water discharged for the day of record and by a conversion factor (usually 0.0027) to obtain tons per day. Tons of sediment per day plotted against water discharge is a sediment-rating curve. When these data are plotted on log-log paper, a straight line is often approximated through a major part of the range of discharge (fig. 3). By using a long-term flow-duration curve or equivalent tabulation[3] with the sediment-rating curve, it is possible to estimate the prevailing annual suspended-sediment yield. This may be adjusted to reflect expected future conditions.

The bedload is not measured by this method and must be estimated and added to the suspended-sediment yield. The bedload ranges from none to as much as 50 pct or more of the total sediment load, depending on the size of sediment available for transport by the stream and other factors.

Usually, the time required to collect enough suspended-load data for a sediment-rating curve makes the installation of a sampling station impractical for the small watersheds involved in SCS programs. In some instances, representative measurements of all ranges of discharge may be obtained in 1 or 2 years, while in others, measurements may be needed for 10 years before a suitable range of discharges occurs to produce a realistic sediment-rating curve.

The infrequent use of this method is due to the short time usually available to make measurements between the planning stage of a project and the final design stage (existing long-term records for small watersheds are rare), and the fact that the relationship between discharge and sediment concentration may vary at a measuring station, depending on the grain-size distribution of sediment transported. If the moving sediment is mostly bedload and is from channel erosion, there is a stronger correlation between sediment concentration and discharge than if the load consists mostly of suspended sediment. The amount of fine sediment in streamflow usually depends more on the intensity and location of rainfall on the watershed, on cover conditions, and on other factors than on water discharge. Generally, the flow transports all the silt- and clay-size sediment available from upland erosion, whereas the flow properties determine the amount and maximum size of available coarser materials that can be transported.

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[2] Flaxman, E. M. 1972. Predicting sediment yield in Western United States. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers 98 (HY12) : 2073–2085.

[3] Anderson, H. W. 1954. Suspended sediment discharge as related to streamflow, topography, soil and land use. Transactions of the American Geophysical Union, 35: 268–281.

Miller, C. R. 1951. Analysis of the flow-duration, sediment-rating curve method of computing sediment yield. U.S. Department of the Interior, Bureau of Reclamation, Denver, Colo., 15 pp.

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SOIL CONSERVATION SERVICE

RESERVOIR SEDIMENTATION DESIGN SUMMARY

WATERSHED ______________________ SITE NO. ________ DRAINAGE AREA ________ Sq. Mi. ________ Acres

LOCATION ______________________ STATE ________ PURPOSE ______________________

DATA COMPUTED BY ______________________ TITLE ______________________ DATE ________

SEDIMENT YIELD BY SOURCES (AVERAGE ANNUAL)

		PRESENT CONDITIONS			FUTURE (AFTER CONS. TREATMENT)		
		ACRES	SOIL LOSS (TONS/AC)	TOTAL (TONS)	ACRES	SOIL LOSS (TONS/AC)	TOTAL (TONS)
SHEET EROSION	CULTIVATED LAND						
	IDLE LAND						
	PASTURE - RANGE						
	WOODLAND						
	OTHER						

	DELIVERY RATIO (%)		TONS DELIVERED	DELIVERY RATIO (%)		TONS DELIVERED
SHEET EROSION - TOTAL						
GULLY EROSION						
STREAMBANK EROSION						
STREAMBED EROSION						
FLOODPLAIN SCOUR						
OTHER (ROADSIDE ETC.)						
		TOTAL			TOTAL	

DEPOSITION

TEXTURE INCOMING SEDIMENT		
% CLAY	% SILT	% COARSE
VOLUME WEIGHT DEPOSITED SEDIMENT LBS/CU. FT.		
SUBMERGED		
AERATED		

	SEDIMENT DELIVERED TO SITE (TONS/YR)	TRAP EFFICIENCY (%)	ANNUAL DEPOSITION (TONS)	DESIGN PERIOD (YRS)	PERIOD DEPOSITION (TONS)	DESIGN DEPOSITION (TONS)
PRESENT						
FUTURE						
FUTURE						
			TOTALS			

SEDIMENT STORAGE REQUIREMENTS

PERIOD (YRS)	CONDITION OF SEDIMENT	% OF TOTAL	DEPOSITION (TONS)	VOLUME WEIGHT	STORAGE REQUIRED		STORAGE ALLOCATION (ACRE FEET)		
				TONS/AC.FT.	ACRE-FEET	WATERSHED INCHES	SEDIMENT POOL	RETARDING POOL	OTHER
	SUBMERGED								
	AERATED								
	SUBMERGED								
	AERATED								
		TOTALS							

FIGURE 2.—Reservoir sedimentation design summary.

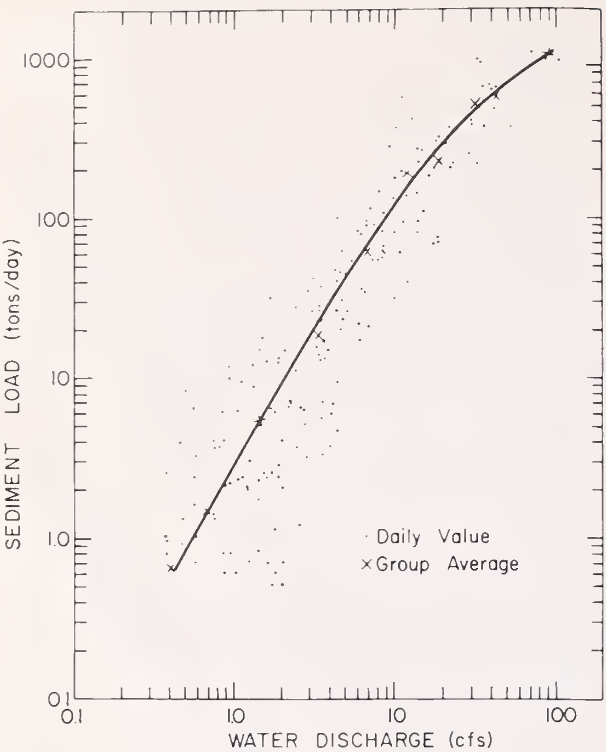

FIGURE 3.—A sediment-rating curve, showing direct runoff versus sediment discharge, by day, Pigeon Roost Creek Watershed 5, January 1957–December 1960. (From Piest, R. F. 1965. The role of the large storm as a sediment contributor. *In* Proceedings of the Federal Inter-Agency Sedimentation Conference 1963, pp. 98–108. U.S. Department of Agriculture Miscellaneous Publication No. 970.)

A principal shortcoming is that suspended-load measurements provide little information on the relative importance of various sources of sediment in the watershed. This information is important in planning land treatment and structural measures in the SCS program to reduce sediment yield, as well as in evaluating the effects of conservation measures on sediment yields. Flaxman suggests that correlations can be made between varying sediment concentrations and varying watershed conditions. Although he concludes that more studies are needed, this procedure may have more application in SCS in the future.

In some places, sediment-yield estimates based on suspended-load records are available from nearby similar watersheds, and these may be used with certain adjustments or restrictions.

4. Measured sediment accumulation, particularly in reservoirs, is usually the best source of data for establishing sediment yields if the record is long enough to be representative. Reservoir sediment deposition and sediment yield, however, are not synonymous. The amount in tons of sediment accumulated must be divided by the trap efficiency of the reservoir to determine the sediment yield. This then would include the amount of sediment (usually fine) that passed on through the reservoir.

The relationship of erosion control, sediment yield, and reservoir sediment accumulation led SCS in July 1934 to begin the first nationwide survey of reservoir capacities and sediment accumulation.[4] SCS has actively surveyed reservoirs in the years since. Summaries of reservoir surveys made by all Federal agencies are compiled and printed periodically by the Sedimentation Committee, now of the Water Resources Council, and are updated every 5 years. In the summary for the period through 1965 (U.S. Department of Agriculture Miscellaneous Publication No. 1143, 1969) about 70 pct of the reservoirs listed were reported by SCS. In terms of capacities surveyed, the SCS proportion is much less impressive. A new summary through 1970 compiled by the Agricultural Research Service (ARS) for the Sedimentation Committee, Water Resources Council, is now available (U.S. Department of Agriculture Miscellaneous Publication No. 1266, 1973).

In 1970 SCS prepared a plan for systematically surveying SCS-designed reservoirs representative of land resource areas. These selected reservoirs are being surveyed every 5 to 10 years and after major storm runoff in an attempt to obtain representative sediment yields, by land resource area, as affected by watershed conditions. One objective is to develop guidelines on expected sediment yields for watersheds for which topography, soils, cover, rainfall, and conservation practices may be comparable. Documentation of the effects of land treatment on sediment yields from these watersheds is another important goal of reservoir surveys.

When a reservoir is being planned in a watershed adjacent to a similar watershed with measured reservoir sediment accumulation, the measurements provide excellent data for predict-

[4] Eakin, H. M. (revised by C. B. Brown). 1939. Silting of reservoirs. U.S. Department of Agriculture Technical Bulletin 524, 168 pp.

ing the yield to the planned reservoir. Since the trap efficiency of the two reservoirs may be different, the sediment accumulation in the measured reservoir must be divided by its trap efficiency to obtain the actual sediment yield. If this yield is transferred to the planned reservoir, it must be multiplied by the anticipated trap efficiency to determine the sediment storage requirement. To transfer sediment yield directly, the watershed conditions not only must be similar, but the size of the drainage area of the surveyed reservoir should be not less than one-half nor more than twice the drainage area for the structures being designed. For drainage areas differing by 10 times or more in size, no attempt should be made to transfer the data. For drainage areas more than twice as large but less than 10 times as large (and reciprocally between one-half and one-tenth as large), the total annual sediment yield may be adjusted for design use on the basis of the relationship:

$$S_e = S_m (A_e/A_m)^{0.8},$$

where S_e=sediment yield to structure being designed, in tons per year,

S_m=sediment yield to the surveyed reservoir, in tons per year (measured annual deposition divided by trap efficiency of surveyed reservoir),

A_e=drainage area of reservoir being designed,

and A_m=drainage area of surveyed reservoir.

The 0.8 power factor is an observed relationship and is based on limited data, since similar watersheds of greatly different sizes are rare.

In certain consistently mountainous areas, such as the Sierra Nevada, there is no indicated difference in sediment yield per unit area due to size of drainage area. Also, where active channel erosion increases downstream (as from main-stem channel-bank cutting), the sediment yield per unit area may increase with increasing drainage area. Therefore, the relationship between drainage area and sediment yield must be adjusted based on experience and is applicable generally to the areas east of the Rocky Mountains.

If the results of reservoir surveys are available, they are used by SCS for design purposes. U.S. Department of Agriculture Miscellaneous Publication No. 1266 lists data from over 1,500 reservoirs surveyed, so that for a given area there may be rates of sediment deposition available for one or several reservoirs. When no reservoirs representative of an area have been surveyed, it is helpful to make sedimentation surveys of suitable existing reservoirs in the area. The reservoirs surveyed or planned for survey to estimate sediment yield should have a record long enough to insure that the data obtained will represent normal or average conditions.

BUREAU OF RECLAMATION PROCEDURES FOR PREDICTING SEDIMENT YIELD

By Robert I. Strand[1]

In the design and operation of water-supply projects, the Bureau of Reclamation needs to estimate sedimentation rates. Some specific concerns associated with sedimentation are loss of capacity in storage reservoirs, size and shape of delta formation, depth of degradation, exclusion and removal requirements at diversion structures, channel stability, and capacity requirements of cross-drainage structures.

FLOW-DURATION, SEDIMENT-RATING CURVE PROCEDURE

Whenever time and funds permit, sediment data collection is initiated early in the project planning procedure. Adequate data for the preparation of a sediment-rating curve can usually be obtained by periodic or miscellaneous sampling if particular emphasis is given to obtaining samples during periods of flood flow. Such a sampling program is considerably less costly than a daily sampling program.

Data for development of the necessary flow-duration curves are usually available from a previously established gaging station that collects project water-supply information. In situations where we do not have water discharge information for a long enough period, we usually correlate the streamflow records with those of a nearby gaging station having a longer period of record.

Figure 1 is a plot of the sediment-discharge rating curves developed from 19 years of sediment sampling data from the San Juan River at Bluff, Utah. As in this case, when the source of runoff may be either snowmelt or rainstorm, it may be necessary to develop individual sediment-rating curves for each of the precipitation seasons.

Figure 2 is a plot of the seasonal flow-duration curves for the same gaging station on the San Juan River. The streamflow records in this instance encompass the same time period as the sediment records. Such parallel records are not often available, the sediment record usually being of short duration with no measurements taken for the extreme flow events. For such cases, extension of the sediment-rating curve becomes an exercise of engineering judgment—which can often be based in part on the maximum observed sediment concentrations.

Figures 3 and 4 are the results of the computed average annual sediment load for the San Juan River and the sediment-yield rate derived from it. The computed sediment yield for the thunderstorm period is 58 pct of the total for the year, although the runoff during that period is only 36 pct of the average annual value.

The validity of the sediment-rating curve can be checked when the suspended-sediment data consist of daily measurements. By using the flow-duration curve(s) for the same period as the period of daily measurement, the loads computed as in figures 3 and 4 should equal the mean annual load for the period of sediment record. If the two do not agree, the sediment-rating curve should be adjusted until agreement is attained.[2] The sediment-rating curve may then be used with the flow-duration curve(s) for the total period of streamflow record to compute the sediment yield for the longer period.

Corrections for the unmeasured portion of the

[1] Hydraulic engineer, Engineering and Research Center, Bureau of Reclamation, U.S. Department of the Interior, Denver, Colo. 80225.

[2] Miller, C. R. 1951. Analysis of flow-duration, sediment-rating curve method of computing sediment yield. U.S. Department of the Interior, Bureau of Reclamation, Denver, Colo., 15 pp.

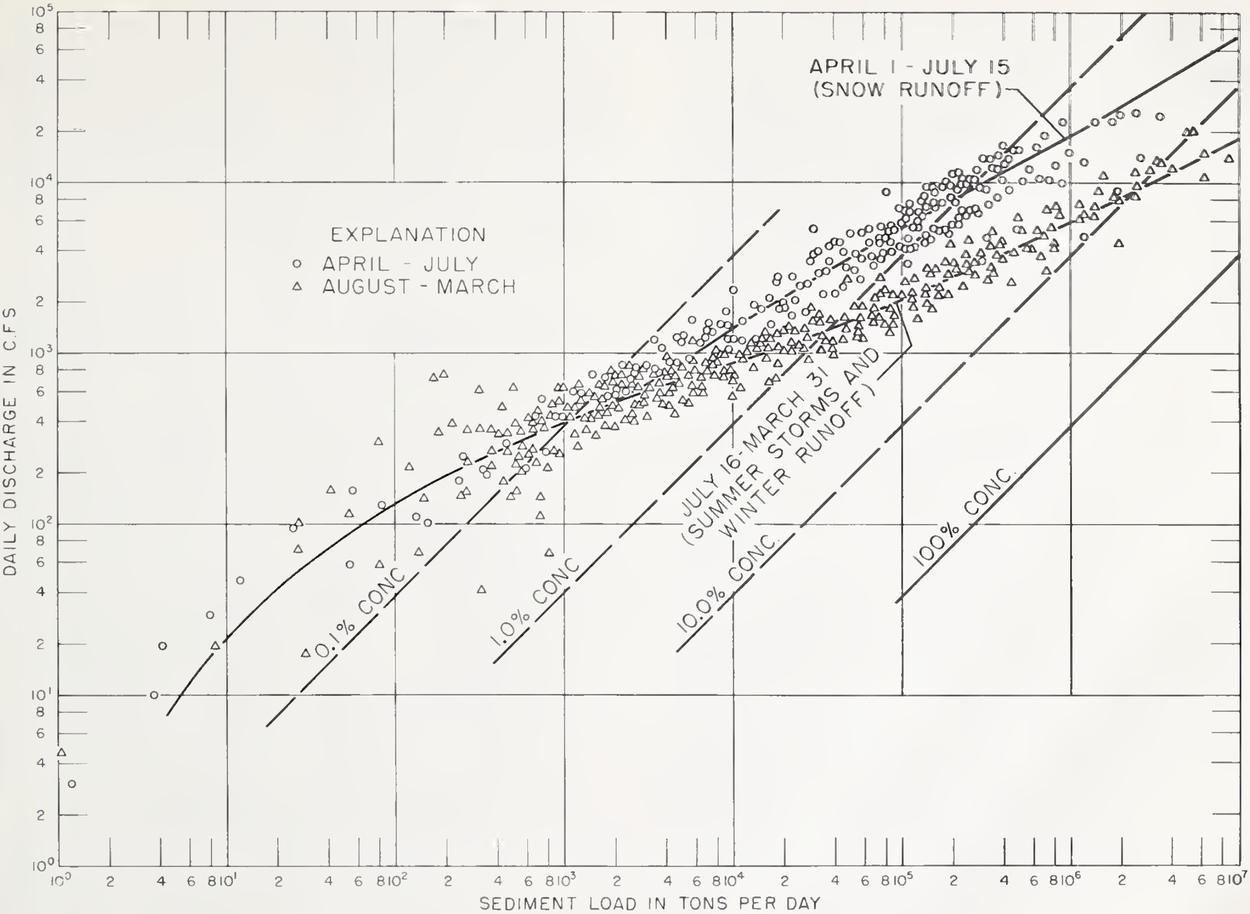

FIGURE 1.—Sediment-discharge rating curves for San Juan River at Bluff, Utah.

TABLE 1.—*Bedload correction table*

Suspended-load concentration (p/m)	Streambed material	Texture of suspended material	Percent bedload in terms of measured suspended load
<1,000	Sand	Similar to bed of stream	25–150
<1,000	Compacted clay, gravel, cobbles and boulders.[1]	Small amount of sand	5– 12
1,000–7,500	Sand	Similar to bed of stream	10– 35
1,000–7,500	Compacted clay, gravel, cobbles and boulders.[1]	25 pct sand or less	5– 12
>7,500	Sand	Similar to bed of stream	2– 8
>7,500	Compacted clay, gravel, cobbles and boulders.[1]	25 pct sand or less	5– 15
Any concentration	Clay and silt, unconsolidated.	Silt and clay	<2

[1] The bed material of the stream may contain any one or all of these very fine or coarse-sized sediments.

sediment load have been made in the results shown in figures 3 and 4. These corrections can be made by using one of the several bedload or total-load formulas available. The Modified Einstein Procedure is most commonly used for estimating total load when channel-hydraulic and suspended-sediment data are available. Total-load computations are made for several discharges and the sediment-rating curve is then adjusted for the quantity of unmeasured load over its entire range.

If sufficient data are not available to make total-load computations, we make adjustments to the suspended-sediment loads using the data shown in table 1.[3] Indeed, the percentages of anticipated bedload shown in this table will indicate the need for collecting data to compute quantities of unmeasured load.

[3] Borland, W. M., and Lane, E. W. 1951. Estimating bed load. Transactions of the American Geophysical Union 32(1): 121.

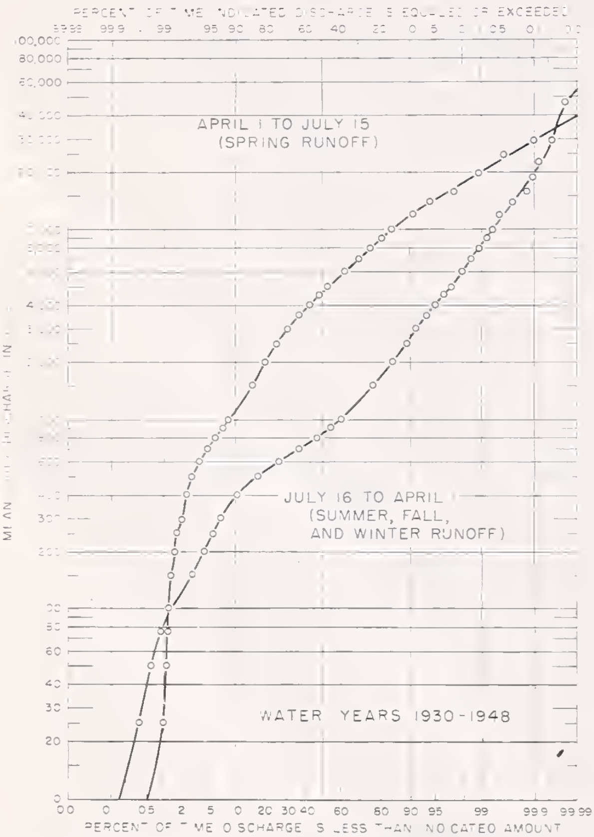

FIGURE 2.—Seasonal flow-duration curves for San Juan River at Bluff, Utah.

SECTION	PERIOD 1930-1948 April 1 to July 15	RIVER San Juon at Bluff
COMPUTED BY	CHECKED BY	DATE 2-19-5

1	2	3	4	5	6	7
% LIMITS	% INTER-VAL	% MID. ORO.	Qw	Os	2x4 Qw DISCH	2x5 Os OISCH.
0.00 - 0.02	0.02	0.01	40,000	3,500,000	8.0	700
0.02 - 0.1	0.08	0.06	32,000	2,400,000	25.6	1,920
0.1 - 0.5	0.4	0.3	25,000	1,550,000	[illegible]	6,200
0.5 - 1.5	1.0	1.0	20,700	1,130,000	207.0	11,300
1.5 - 5.0	3.5	3.25	16,300	740,000	570.5	20,450
5 - 15	10	10	11,700	400,000	1,170.0	40,000
15 - 25	10	20	8,900	245,000	890.0	24,500
25 - 35	10	30	7,000	157,000	700.0	5,700
35 - 45	10	40	5,650	107,000	565.0	10,700
45 - 55	10	50	4,720	79,000	472.0	7,900
55 - 65	10	60	3,750	52,000	375.0	5,200
65 - 75	10	70	2,940	33,500	294.0	3,350
75 - 85	10	80	1,950	7,000	95.0	1,700
85 - 95	10	90	1,100	7,000	110.0	700
95 - 98.5	3.5	96.75	540	2,100	18.9	74
98.5 - 99.5	1.0	99.00	25	2	0.25	0.02
99.5 - 99.9	0.4	99.7	7.5	4.5	0.03	0.02
99.9 - 99.98	0.08	99.94	2.5	2.0	0.02	0.0
99.98 - 100	0.02	99.99	0	0	0	0
				TOTAL	5,702.5	50,394

RUNOFF = 5,702.5 X 06 X 1.9835 = [illegible],200,000 A F/YR

SEDIMENT = 50,394 X 06 = 15,950,000 TONS/YR

UNMEASURED CORRECTION (20%) = 3,200,000 TONS/YR

TOTAL SEDIMENT = 19,150,000 TONS/YR

$$\text{YIELD} = \frac{19,150,000 \text{ TONS/YR}}{1361 \text{ TONS/A F} \times 23,000 \text{ MI}^2} = 0.612 \text{ A F/MI}^2\text{/YR.}$$

FIGURE 3.—Average annual sediment load for the San Juan River snowmelt season.

SEDIMENT-YIELD RATE CURVES

By using reservoir resurvey information or long-term sampling data from watersheds having similar climatic, topographic, and geologic properties, it is possible to construct sediment-yield rate curves. Figure 5 is such a curve developed for the arid Southwest with drainage basin size as the independent variable. The relationship of sediment yield varying with approximately the 0.8 power of drainage area agrees with other findings.[4]

Application of this type of curve should be tempered with judgment based on a thorough knowledge of the drainage basin in question. Recent fires, mining activity, overgrazing, or other

[4] Chow, V. T. 1964. Handbook of applied hydrology, pp. 17.12–17.13. McGraw-Hill, New York.

SECTION	PERIOD 1930-1948 July 16 to April 1	RIVER San Juan at Bluff
COMPUTED BY	CHECKED BY	DATE 2-19-51

1	2	3	4	5	6	7
% LIMITS	% INTER-VAL	% MID. ORD.	Qw	Os	2x4 Ow. DISCH.	2x5 Os. DISCH
0.00 - 0.02	0.02	0.01	56,000	78,000,000	11.2	15,600
0.02 - 0.1	0.08	0.06	24,800	16,000,000	19.84	13,000
0.1 - 0.5	0.4	0.3	13,200	5,100,000	52.8	20,400
0.5 - 1.5	1.0	1.0	8,300	2,000,000	83.0	20,000
1.5 - 5.0	3.5	3.25	4,800	630,000	168.0	22,000
5 - 15	10	10	2,650	117,500	265.0	11,750
15 - 25	10	20	1,660	60,000	166.0	6,000
25 - 35	10	30	1,230	28,000	123.0	2,800
35 - 45	10	40	985	14,700	98.5	1,470
45 - 55	10	50	830	8,700	83.0	870
55 - 65	10	60	730	5,600	73.0	560
65 - 75	10	70	640	3,900	64.0	390
75 - 85	10	80	530	2,500	53.0	225
85 - 95	10	90	378	960	37.8	96
95 - 98.5	3.5	96.75	165	160	5.8	5.6
98.5 - 99.5	1.0	99.00	79	47	0.8	0.5
99.5 - 99.9	0.4	99.7	19.5	9.4	0.08	0.04
99.9 - 99.98	0.08	99.94	4.0	2.8	0.01	0.0
99.98 - 100	0.02	99.99	0	0	0	0
				TOTAL	1,304.8	93,167

RUNOFF = 1,304.8 X 259 X 1.9835 = 670,000 A.F./YR

SEDIMENT = 93,167 X 259 = 24,100,000 TONS/YR

UNMEASURED CORRECTION (10%) = 2,410,000 TONS/YR.

TOTAL SEDIMENT = 26,510,000 TONS/YR

$$\text{YIELD} = \frac{26{,}510{,}000 \text{ TONS/YR}}{1361 \text{ TONS/A.F.} \times 23{,}000 \text{ MI}^2} = 0.847 \text{ A.F./MI}^2\text{/YR}$$

Figure 4.—Average annual sediment load for the San Juan River rainstorm season.

unnatural conditions could seriously upset the predictions, especially on smaller basins.

In locating the pumping-plant intake channel on Lake Havasu, a feature of the Central Arizona Project, we had to determine the sediment inflow to the reservoir from the Bill Williams River. From the time Parker Dam was closed in 1938 through 1968, the Bill Williams arm of Lake Havasu collected deposits from an area of 5,440 mi^2. When Alamo Dam, upstream of Lake Havasu, was closed in July 1968, the directly contributing drainage area was reduced to 710 mi^2. Using the results of a reservoir resurvey on the Bill Williams River arm of Lake Havasu in August 1970, a sediment yield rate of 0.13 acre-foot/mi^2/yr was determined for the total basin prior to construction of Alamo Dam. Plotting this value on the relationship of sediment yield given in figure 5 and drawing a line parallel to the previous curve for the southwest region, a yield is obtained for 710 mi^2 of 0.20 acre-foot/mi^2/yr. This value was checked by comparing it to recommendations of the Pacific Southwest Interagency Committee, and by applying a maximum sediment concentration to the flood flows estimated to occur between Alamo Dam and Lake Havasu. The sediment yield from the drainage basin was added to an estimated sediment volume

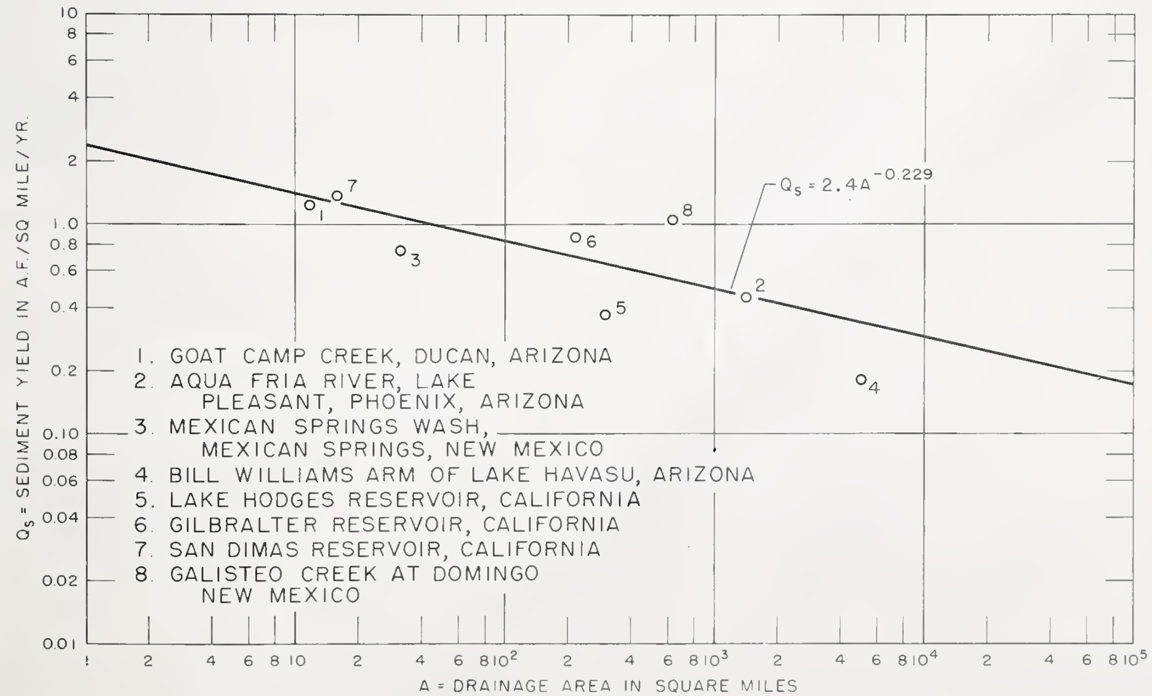

Figure 5.—Sediment yield versus drainage area for the Southwest.

due to degradation below Alamo Dam to give a total sediment inflow to Lake Havasu for the project life. In our analysis of degradation we assumed that the only flows which would erode sediment from the channel would be spills from Alamo Dam, which will occur, on an average, about 2.4 times/yr. Using Colby's relationship of sand transport to velocity,[5] after a check of the computations for historic conditions, we computed a sand transport for future flows of 28,000 tons/d or 3,200 acre-feet for the 100-yr project life. With this amount added the total sediment inflow to Lake Havasu for the project life was 17,400 acre-feet.

OTHER METHODS

The prediction of sediment yield from the small drainage systems intersected by our conveyance systems is one of the more difficult procedures. Cross-drainage structures must be designed to accommodate the passage of the design-frequency flood and its associated sediment volume. An average sediment concentration is assumed for the design flood volume and the volume of sediment that may be deposited at the structure is derived. The assumption of concentration is usually based on a sampled concentration from a similar stream in the area.

In the design of the drainage system for the Navajo Indian Irrigation Project in the San Juan Basin of northern New Mexico, we estimated sediment volumes for 42 cross-drainage areas above one of the large drains, ranging in size from 7 to 3,200 acres. The drain was designed to exclude sediment contributed by cross-drainage channels and to store on the land all sediment associated with floods less than or equal to the design flood.

The development plan called for operating the drain for several years before full development of farm units within the drainage areas. Therefore, two conditions of ground cover were considered for lands above the drain, one being the natural state in which the land is quite barren and highly erodible, and the other with farm units well-developed, including good crop cover, field drains, and farm roads. Assuming natural conditions above the drain, we estimated a mean sediment concentration for flood events over a 100-yr period. This concentration was then applied to the design flood for each drainage area to determine the accompanying sediment volume. For the condition of completed project development, we distinguished between irrigated farmland and undeveloped land, applying the same sediment concentration to undeveloped land and an adjusted concentration for irrigated land. An adjustment factor was derived making use of the universal soil loss equation, as defined in U.S. Department of Agriculture Agriculture Handbook No. 282, together with the sediment-yield rate curve for the Southwest shown in figure 5. The method used in making this adjustment is shown in the example below. This procedure involved some rough estimates of the soil loss parameters and at best provides only an approximation of sediment volumes that can be expected. The example does serve to underscore our need for more data on sediment yield from small watersheds, especially from the arid regions of the West where many of the reclamation projects are located.

Total sediment volume from area No. 15 for 100-yr flood event.

F_T=100-yr flood volume=92.0 acre-feet.

A_T=total drainage area=897.6 acres=1.402 mi^2
A_I=irrigated area =409.0 acres= .639 mi^2
A_N=nonirrigated area =488.6 acres= .763 mi^2

Yield rate on irrigated land=0.39 acre-feet/mi^2/yr.
Yield rate on nonirrigated land=2.20 acre-feet/mi^2/yr.

Ratio of rates=0.39/2.20=0.1772.

C_N=concentration from nonirrigated land =0.20.
C_I=conventration from irrigated land=0.1772 $\times$0.20=0.0354.

$$\text{Sediment volume} = F_T/A_T\,(A_N C_N + A_I C_I)$$
$$= 92.0/897.6\,(488.6\times 0.20) + (409.0\times 0.0354)$$
$$= 11.50 \text{ acre-feet.}$$

We have attempted to use some of the sedi-

[5] Colby, Bruce R. 1964. Discharge of sands and mean velocity relationships in sand-bed streams. U.S. Geological Survey Professional Paper No. 462-A.

ment-yield predictive equations based upon quantification of the factors influencing sediment production.[6] Our utilization of these equations has been limited to checking the results of sedimentation yields obtained by other methods. These comparisons have not always been consistent. The difficulty appears to be the realistic quantification of the variables when the drainage basins are relatively large and there is considerable variation within the basin.

[6] Pacific Southwest Interagency Committee. 1968. Factors affecting sediment yield and measures for the reduction of erosion and sediment yield, pp. 1–10.

CONCLUSIONS

The techniques described in this report and utilized by the Bureau of Reclamation for predicting sediment yields vary considerably depending upon the data available and the complexity of the problem. In those instances involving large reservoirs with large drainage areas, where sediment inflow is significant, we would use the flow-duration, sediment-rating curve procedure with the necessary corrections for unmeasured load. However, each situation is unique; when the problem is complicated, as by an upstream dam, the technique must be adjusted to fit.

CORPS OF ENGINEERS METHODS FOR PREDICTING SEDIMENT YIELDS

By Robert H. Livesey[1]

INTRODUCTION

The methods used by the Corps of Engineers for predicting sediment yields are in general, based upon empirical relationships, but vary in scope and procedure depending upon the complexity of the individual water resource project plan or design. Because of the diverse nature of these projects, both in design magnitude and geographic location, a standard method for design application is not employed throughout the Corps. Instead, the individual district offices make a sensitivity appraisal to evaluate the impact of all sedimentation influences on a specific project plan. From this first-approximation analysis, the scope of the sedimentation problem is defined. This definition then becomes the basis for selecting methods to be used in establishing the true magnitude of the problem components and design solution criteria. Where it is apparent that modification of a method might be practical to produce an improvement in design evaluation, such modification is encouraged. For this reason, a variety of procedures is developed and employed throughout the Corps, but they all relate closely to one of the three basic empirical approaches for predicting sediment yield, namely, (1) measuring the yield rate directly by sediment sampling or reservoir surveys, (2) extrapolation of such measured data to unmeasured drainages by various correlation and probability techniques, or (3) establishment of identifiable physiographic watershed or streamflow characteristics that permit development of predictive equations. Theoretical approaches to the prediction of sediment yields have been occasionally employed for special circumstances where empirical relationships were weak or confidence lacking, but such procedures are not common.

DEVELOPMENT OF PREDICTION METHODS

Sediment sampling in the United States dates back to 1838, when the Corps of Engineers was engaged in navigation channel work on the lower Mississippi River. During the next 100 years, the need for sediment predictions related almost entirely to river navigation and estuary maintenance work. It was not until after passage of the Flood Control Acts of 1928 and 1936, when the Corps started to plan, design, and construct multiple-purpose reservoirs, that the need for sediment-yield predictions developed. Typical of this initial phase of sediment yield investigations was Straub's work, which is well documented in the 1933 Missouri River Basin report of the Chief of Engineers in response to House Document No. 308, 69th Congress. His development of the sediment-rating curve method was later amplified by Campbell and Bauder in the 1940's, and Miller in the 1950's, into the popular rating curve-flow duration method. After Straub's work the emphasis on documenting sediment-yield rates shifted in the 1940's to reservoir survey measurements and the relation of sediment yield to contributing drainage areas, reservoir capacities, stream density or slope, and runoff. The early work of Brown and Gottschalk is typical of this period. But this work, like Straub's, was considered professionally weak because it related sediment yield to only a few of the many contributing factors. Next, during the early 1950's, efforts were concentrated on the expansion of Musgrave's definition of quantitative factors for small land units to the drainage increments of large river control projects. These evaluations attempted, without much success, to relate many of Musgrave's factors on a regional or annual

[1] Supervisory hydraulic engineer, Omaha District, U.S. Army Corps of Engineers, Omaha, Nebr. 68102.

basis in lieu of local or seasonal definitions. During this same period, sediment sampling and reservoir survey measurement techniques were enhanced. Long-term basin runoff characteristics were also identified to improve confidence in the sediment rating curve-flow duration method. However, by the late 1950's, a shift in project planning to smaller drainage areas began. The definition of local drainage controls and urban runoff assumed greater importance; the "big dam" criteria for yield predictions were no longer applicable. This change required a downward extrapolation toward the upper limits of SCS criteria. To meet the need, the number of Corps sediment-load stations was doubled, plans were implemented to document urban runoff characteristics, and correlation techniques concentrated on qualifying the adequacy of short-term records. As the environmental issues of the late 1960's developed their impetus, design criteria and needs mushroomed into the broad fields of water quality control, biological reproduction, eutrophication acceleration, and, most recently, waste-water management. Prediction methods for most of these latter aspects remain unqualified at the present time.

PREDICTION CRITERION

Corps study investigation or design criterion for individual projects dictates that alternative methods for sediment-yield prediction be considered and evaluated. These empirical methods generally fall into two basic categories, the extrapolation of measured records and the use of predictive equations. Most work related to the planning, design and operation of reservoirs is based upon the former method, while channel alinement and stabilization relate to the latter method. Although the Corps has no standard method, the use of the sediment rating curve-flow duration technique, or some ramification, has had the widest application. The following discussion of the various sediment-yield prediction methods used in Corps of Engineers studies and designs will be divided into the two basic categories previously mentioned. Descriptive comments will be limited to a summary nature, but a study or design memorandum reference is given for each method. Most references can provide complete details on one or more methods. An attempt was made to include with each discussion a reference figure that identified the salient features of the method or the output results.

Before a discussion of the characteristics of various methods, some comment must be focused on the appraisal techniques used to select the alternative methods to be considered. The following are common project evaluation criteria:

Sensitivity Evaluation.—This appraisal attempts to bring the scope of sedimentation influences into focus with the overall project purpose and plan. Later detailed analyses define the real magnitude and occasionally dictate a shift in study emphasis; but, early in both the planning and design phases, potential problems are identified and priorities established regarding their importance to the various design features. When considering current environmental aspects, it is not uncommon to schedule a later, second sensitivity evaluation in case a reorientation of project priorities or efforts is necessary.

Identifying Basic Data.—This operation consists of a records and literature search to find existing streamflow or sediment measurement records, previous related study data or pertinent research activity.

Hydrology.—This analysis usually constitutes the initial design effort. Early in this work preliminary sediment-yield predictions are made to satisfy first-approximation storage and flow-routing requirements. Later, as alternate project operation schemes are developed, the design yield rates are incorporated into the final hydrologic analysis. The development of long-term flow-duration data is another important contribution.

Geomorphic Characteristics.—The factors considered in this analysis are quite varied and broad; the degree of investigation depends upon need. General needs include such items as geologic variations, soil classifications and characteristics, channel dimensions, composition of stream bank and bed materials and stream slopes.

Basin Reconnaissance.—At least one field reconnaissance of the contributing drainage is made early in the preliminary design phase. Usually it is a "windshield" survey of sufficient scope to identify major or contrasting drainage features and permit judgment comparison of variations in yield rates and channel dimensions.

METHODS INVOLVING EXTRAPOLATION OF MEASURED RECORDS

The first category involves the extrapolation of measured records and is divided into three major measurement classifications—sediment loads, reservoir surveys, and reconnaissance inspections. Relevant methods for each are described below.

Sediment-Load Measurements

Sediment Rating Curve Method.—This basic, older method is usually associated with a flow-duration analysis, but occasionally special circumstances still require its use. An example would involve instantaneous units of flow and concentration rather than mean daily values. These applications usually relate to a near-constant or limited range of flows, such as for seasonal or monthly variations between run-of-river reservoirs within a large system. In such instances the minor incremental flow and sediment contributions, including their duration and frequency, are usually obscured by the large base flow. The method involves the plotting of measured suspended-sediment load values versus equivalent units of discharge for desired time periods and defining the mean curve. An example is shown in figure 1. This method was originally developed for the 1933 Missouri River Basin 308 report with further enhancement by Campbell and Bauder in their paper, "A Rating-Curve Method for Determining Silt-Discharge of Streams," published in the Transactions of the American Geophysical Union (Vol. 30, August 1949).

Sediment Rating Curve-Flow Duration Method.—This popular method combines the rating-curve principle with the measured stream-flow record to develop a probability correlation between the sediment and water discharge of a stream. The method consists of a determination of suspended-sediment load values from the rating curve for corresponding increments of discharge from a flow-duration curve. Multiplication of the suspended-sediment load and discharge increments by the time percentage inter-

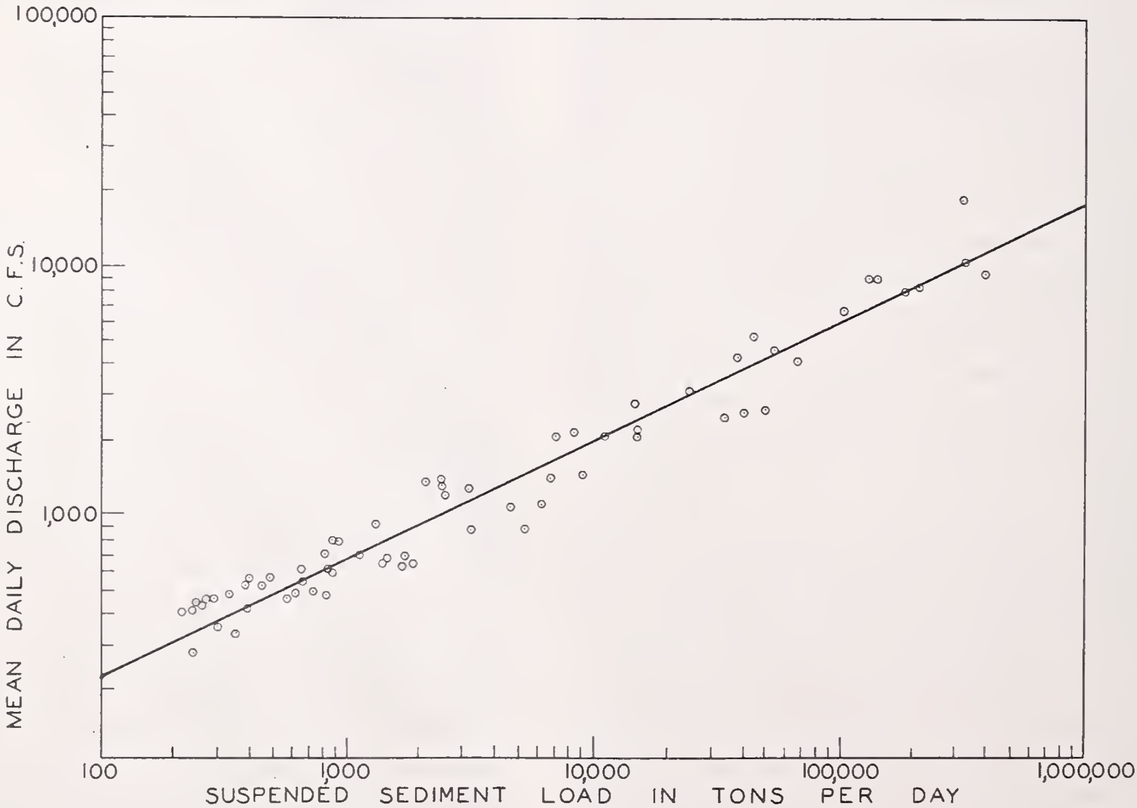

FIGURE 1.—Sediment-rating curve, Elkhorn River, Waterloo, Nebr.

val gives a daily occurrence value. Totaling these daily average values produces the mean daily discharge and suspended-sediment load for the year. Further multiplication of these mean daily values by the number of days in the year gives average annual rates. Addition of unmeasured suspended or bedload estimates results in a total average annual sediment-load value. Variations in this method permit development of long-term rate estimates based upon seasonal or short periods of record. Figures 1, 2, and 3 record the principle details of this method. For more complete details, including an evaluation of the techniques of this method, see "An Analysis of the Flow-Duration, Sediment-Rating Curve Method of Computing Sediment Yield," by Carl R. Miller, published by the Bureau of Reclamation's Hydrology Branch, Denver, Colo., in April 1951.

Sediment Discharge-Soil Type Relationships.—This method relies upon a runoff-sediment load record to obtain a correlation of sediment yield according to soil classification and cultivated areas. River basins are divided by soil types and annual surface runoff-sediment discharge curves developed for each classification according to the extent of cultivated acreage. An example of the relationship developed for 13 drainages of mixed loess and glacial soils is shown in figure 4. A comparable correlation was possible for residual limestone, sandstone, and shale soils, but in loessial terrain the results were indeterminate. For further information refer to an unpublished report on "Rates of Sediment Production in the Kansas City District," by A. L. Hill, available from the U.S. Army Engineer District, Kansas City, Kansas City, Mo. 69106.

Dominant Basin Characteristics.—The similarity of the dominant physical characteristics of a drainage basin versus the measured sediment production is the basis for this method. The dominant characteristics included land use, relief and topography, climate, water, and soil types. Land-resource areas are used to group the defined individual sediment yield rates into comparable area categories. Both suspended-sediment load and reservoir sedimentation survey records are used to establish yield rates by drainage area or time increments for a given base period. The flow-duration principle is applied to adjust short-term records to the base period. Such adjustments require establishment of sediment discharge-to-streamflow relationships for the period of measurements and then correlating this data to the long-term flow regimen of the stream. The method has produced indications of sediment-yield trends with time in several instances. Figures 5, 6, and 7 depict the general features of this method. For details see "Sediment Yields in the Upper Mississippi River Basin," by Frank J. Mack, published in the "Proceedings of a Seminar on Sediment Transport in Rivers and Reservoirs" in April 1970 by the Hydrologic Engineering Center, Corps of Engineers, at Davis, Calif.

Sediment Yield by Isogram Intervals.—Except for the degree of individual basin analysis, a similarity exists between this and the preceding method. This method recognizes the dominant physical characteristics and measured sediment-production records of the basin, but in addition, relies upon personal knowledge and engineering judgment to evaluate the sediment-yield characteristics of a basin. The method was developed for use as a task force expedient by a group of interagency sedimentation specialists to document sediment-yield rates for large river basins. Yield rates for standard periods of time are derived by extrapolation of shorter period records by one of three procedures—comparing sediment load-water discharge relations between periods of record and the standard period, derivation of sediment-water regression curves for increments of drainage area, or evaluating relations between intermittent sediment measurements made over short time periods. The final delineation of isogram lines is based upon group experience and judgment. A typical end-product of this method is shown on figure 8. Examples of this method can be found in any one of the seven subbasin sedimentation reports prepared by the Task Force on Sedimentation for the Missouri River Basin Comprehensive Framework Study, submitted for limited distribution to participating agencies of the Missouri Basin Inter-Agency Committee in 1968 and 1969.

Sediment Yield During Urban Expansion.—The techniques of this method are still in the developmental stage. The basic premise in the transition of rural lands to urban usage over given time periods is that sediment-yield rates accelerate from agricultural values to a high peak during landscaping or construction, then decline to a lower plateau as the land "heals,"

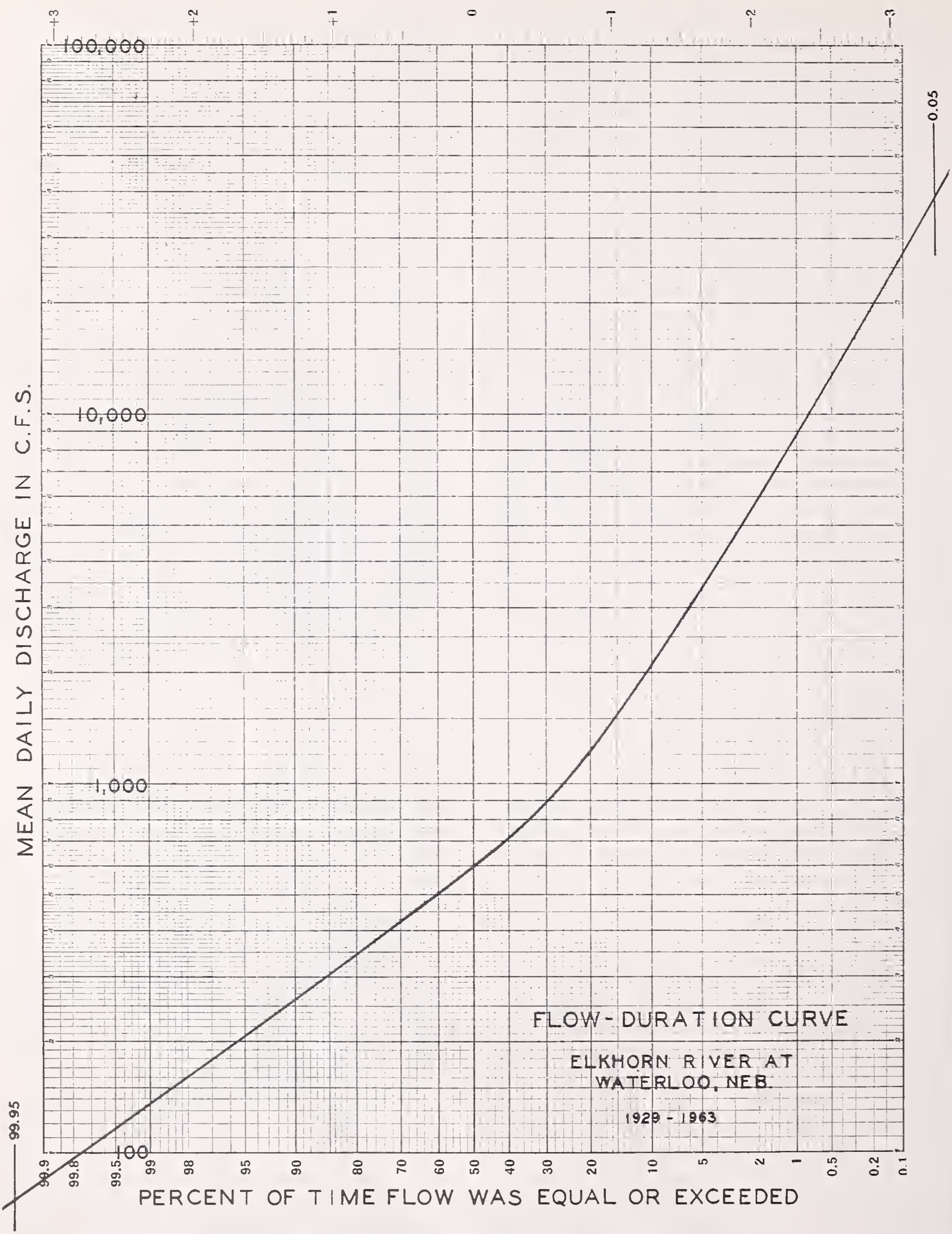

FIGURE 2.—Flow-duration curve, Elkhorn River, Waterloo, Nebr.

LONG TERM TOTAL SEDIMENT LOAD ESTIMATE FOR
ELKHORN RIVER AT WATERLOO, NEBRASKA

STREAMFLOW RECORD - 1929 TO 1963
SUSPENDED SEDIMENT SAMPLING RECORD - AUG. 1948 TO NOV. 1950

Percent Mid Ord.	Percent Incre-ment	Water Discharge Q_w (cfs)	Suspended Sediment Load Q_s (tons)	Daily Average Q_w (cfs)	Daily Average Q_s (tons)
0.05	0.1	37,000	4,500,000	37.0	4500
0.3	0.4	15,000	680,000	60.0	2720
1.0	1.0	9,000	230,000	90.0	2300
3.25	3.5	4,500	55,000	157.5	1925
10	10	2,100	11,000	210.0	1100
20	10	1,200	3,500	120.0	350
30	10	880	1,800	88.0	180
40	10	710	1,150	71.0	115
50	10	600	800	60.0	80
60	10	510	580	51.0	58
70	10	425	390	42.5	39
80	10	345	250	34.5	25
90	10	260	140	26.0	14
96.75	3.5	180	64	6.3	2
99.0	1.0	135	35	1.4	1
99.7	0.4	105	20	0.4	0
99.95	0.1	74	13	0.1	0
		Totals		1055.7	13,409

Annual Q_w = 1055.7 x 365 x 1.98 = 762,950 AF/Yr

Annual Q_s = 13,409 x 365 = 4,894,000 tons/yr

Unmeasured & bed load = 10% Qs = 489,000 tons/yr

Total sediment load = 5,383,000 tons/yr

Total Drainage Area = 6,900 square miles

Sediment Contributing D.A. = 5,900 square miles

Average Annual Sediment Yield = 912 tons/square mile

FIGURE 3.—Rating-curve-flow duration method. Elkhorn River, Waterloo, Nebr.

and finally level off at some low stable rate representative of business or residential lands. A projection of urban expansion limits, provided by the local metropolitan planning authority, serves as a base for converting contributing drainages from rural use to single family, multifamily or commercial usage. Integration of yield rates for increments of area in various stages of development permits a continuous assessment over the design life of the project. Judgmental extrapolation of limited urban runoff and sediment-yield measurements is currently necessary, but data collection programs that concentrate on storm-runoff measurements can quickly improve this limitation. A generalized schematic outline of this method, as being developed by the Omaha District, is shown in figures 9 and 10.

Reservoir Sedimentation Surveys

Sediment Yield Per Unit of Drainage.—The application of this method is widespread because of its simplicity in relating measured rates of sediment yield to the contributing drainage area increment. Numerous correlations are possible within certain ranges of drainage area by soil types, runoff volumes, watershed-capacity ratios, dominant discharge, land use, physiographic areas, and many other parameters. Most Corps applications of these yield rates pertain to contributing drainages greater than 100 mi^2, so correlation with the conventional soil loss parameters is not common. The principle source of reference data is U.S. Department of Agriculture Miscellaneous Publication No. 1143, "Summary of Reservoir Sediment Deposition Surveys Made in the United States Through 1965," or related reporting form 1787. A typical example of this method can be noted in figure 11.

Yield Production for Debris Basins.—This is a special application used to determine the sediment yield into flood control debris basins in mountainous terrain. The method was developed from observed debris volumes that reflect ground conditions influenced by prior rain runoff and areas subjected to partial or complete "burns." Influencing factors include size and shape of drainage area; steepness of canyons and side slopes; geological characteristics; type and density of plant cover; recency of burns; and frequency, duration, and intensity of storms. Measured debris volumes are adjusted to a common base and curves developed for separate corrections of the major factors affecting debris production. Figure 12 summarizes the details of this method. Further information is available in "A Method of Estimating Debris-Storage Requirements for Debris Basins," by Fred E. Tatum, published in the "Proceedings of the 1963 Federal Inter-Agency Sedimentation Conference," U.S. Department of Agriculture Miscellaneous Publication No. 970.

Reconnaissance Inspections

The following methods are directed toward establishing preliminary estimates of sediment yield for large drainage areas. On occasion, the investigation details have been expanded to cover studies of design scope for small to moderate drainages. Their basic premise consists of a quick but detailed reconnaissance inspection of the contributing drainage area by two or more sedimentation specialists, who, by experience, are capable of making estimates of sediment yield rates. During the field reconnaissance they collectively establish representative point rates for

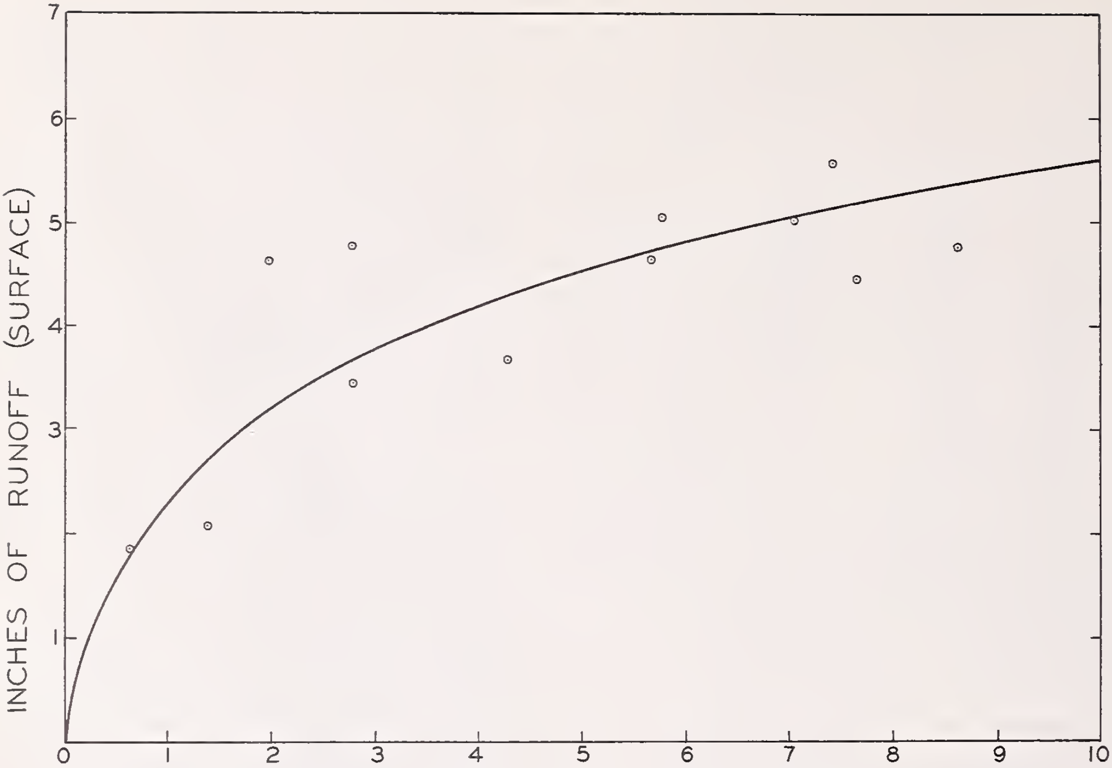

FIGURE 4.—Average annual runoff for mixed loess and glacial soils.

increments of major drainages within the overall study basin. This technique is particularly applicable for a degree assessment of contributing versus noncontributing drainage as influenced by soil management practices, smaller reservoirs or ponds, or irrigation diversion projects. If the basin is relatively small, perhaps less than 1,000 mi^2, the estimates for even third- or fourth-order streams can become quite detailed. For larger basins, selected streams might be covered in more detail and the remainder left to a random choice of inspection. The end product is usually similar to that shown in figure 8.

Interpolation of Rates Within a Basin.—This method requires several points of measured sediment yield, by either sediment sampling or reservoir surveys, within the basin drainage. One of these points should be located near the mouth of the basin to reflect the total measured yield from the drainage. During the field reconnaissance these measured rates are used as a comparative guide for estimating yield rates for small increments of the unmeasured drainages. When enough point estimates are established, a yield contour map is developed. Using digitizing or planimetering processes, drainage area increments of equal yield rates are totaled for the major drainages within the basin. A summation of these totals and division by the contributing drainage-area value gives an average sediment-yield rate for the subject increment. These increment rates are checked against the measured increment rates for verification. If they are not reasonably comparable, adjustments to selected point estimates are justified to bring the integrated total into balance with measured data.

Extrapolation to Unmeasured Watersheds.—The basic procedure is similar to that above except that a comparison between the total estimated and measured rates for a basin is not possible. Prior to the field inspection of the unmeasured drainage, the reconnaissance team usually makes a preliminary inspection of the measured drainages being used as the extrapolation base. This visual inspection requires additional time and effort but serves as an effective means for comparative extrapolation. The validity of this method is dependent upon the degree of extrapolation, but apparent satisfactory results have been produced within a restricted time period.

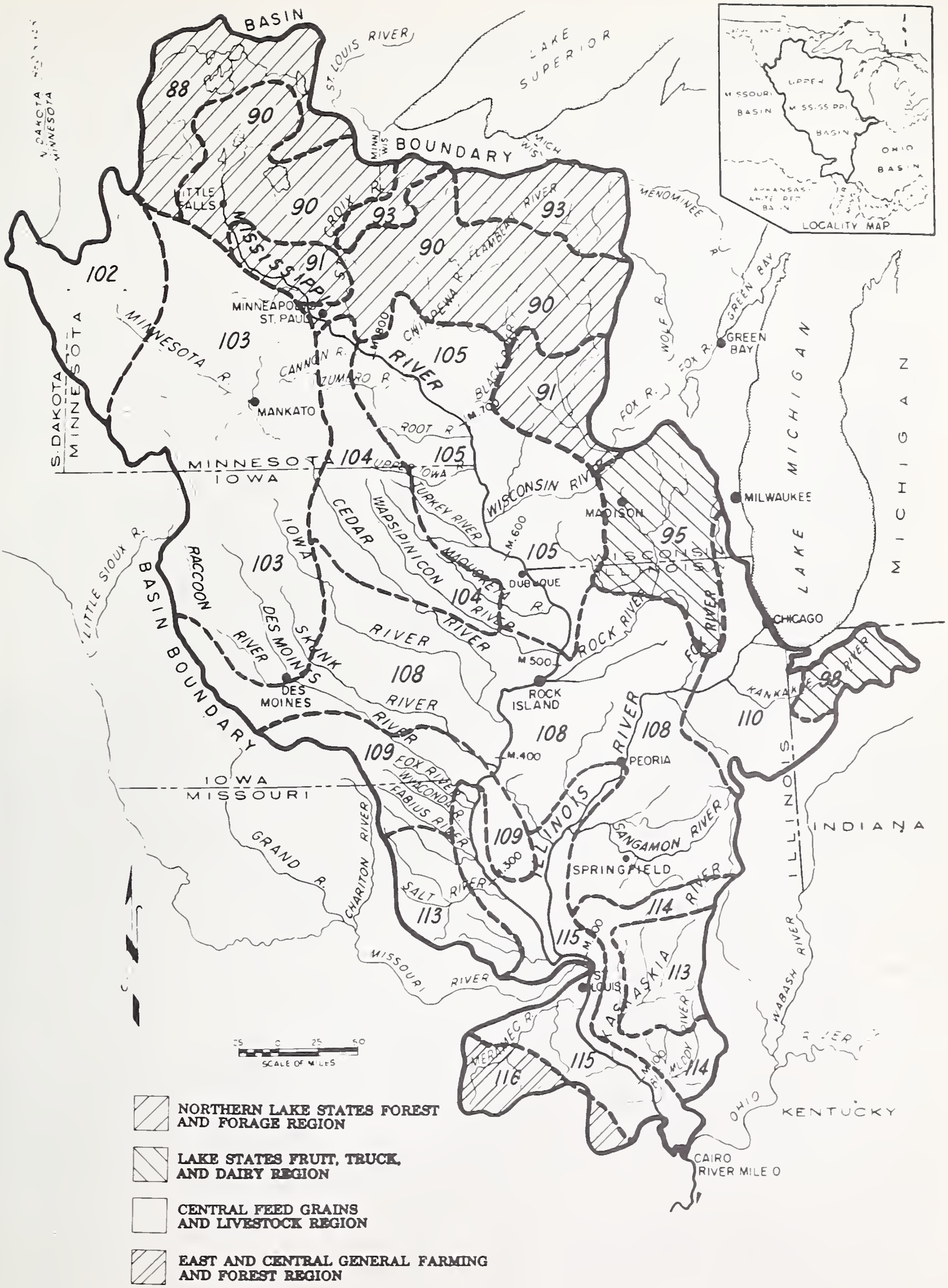

FIGURE 5.—Land-resource regions and major land-resource areas.

FIGURE 6.—Location of basic data.

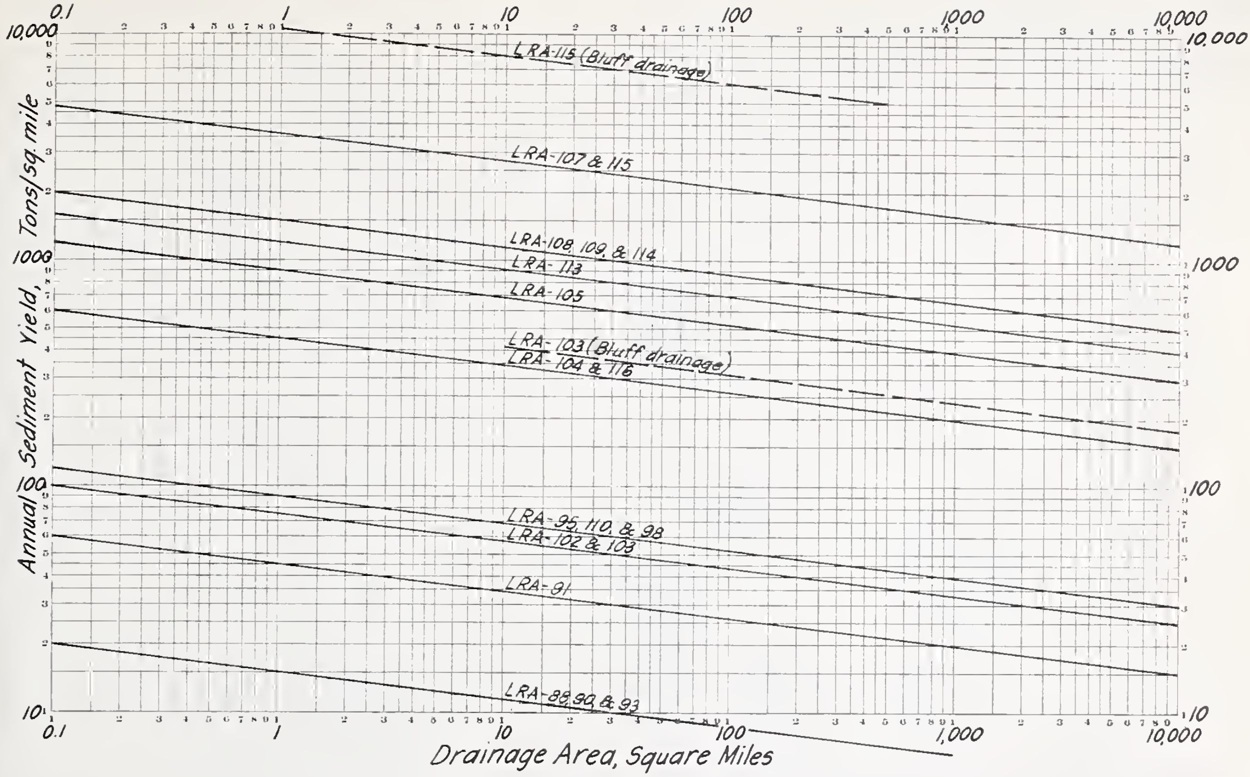

FIGURE 7.—Observed sediment yields, all land-resource areas.

METHODS INVOLVING PREDICTIVE EQUATIONS

The second category involves predictive equation methods. Most of the individual methods discussed below apply to the solution of specific problems. They differ from the preceding methods in that the predicted sediment yield relates primarily to channel contributions rather than from a watershed drainage. The Corps' use of predictive equations for determining watershed yields is very limited.

Sediment Transport Relationships.—There is a variety of methods in this classification but the most common is the Einstein approach, with one of its many modifications, or the more recent Toffaleti procedure. Their use for sediment-yield predictions usually relates to channel stabilization projects involving aggradation or degradation problems. But their application is also common in establishing the magnitude or rate of unmeasured suspended or bed sediment load values. Estimates of such values are extremely important in certain instances when establishing yield rates from measured suspended-sediment load records, as is required in the rating curve-flow duration method. An excellent discussion of the Einstein and Toffaleti methods, plus others, and a listing of complete references can be found in the Journal of the Hydraulics Division of the American Society of Civil Engineers, April 1971, in Paper 8076, "Sediment Transportation Mechanics: Sediment Discharge Formulas."

Detention-Time Method.—This method is used to predict the volume of sediment passing through a series of run-of-the-river reservoir projects. It is based upon empirical relationships between the detention time of flows passing through the reservoir system and the percentage of sediment deposited. Detention time is defined as the ratio of reservoir storage to the inflow discharge at any given time. Curves of detention time versus percent of wash load and bed-material load deposited are developed to determine deposition-flow through volumes for incremental reaches. As the reservoir volume is depleted by deposition, the detention time is reduced and the yield rate per unit of flow increases. Figure 13 shows a typical relationship between detention time in hours and percent of load deposited for a

FIGURE 8.—Western Dakota tributaries subbasin No. 3. Sediment yield from areas in excess of 100 mi².

series of reservoirs. Reference details for this method can be found in Dardanelle Reservoir Design Memorandum No. 6, Part IV, "Sedimentation," prepared in October 1957 by the Little Rock District.

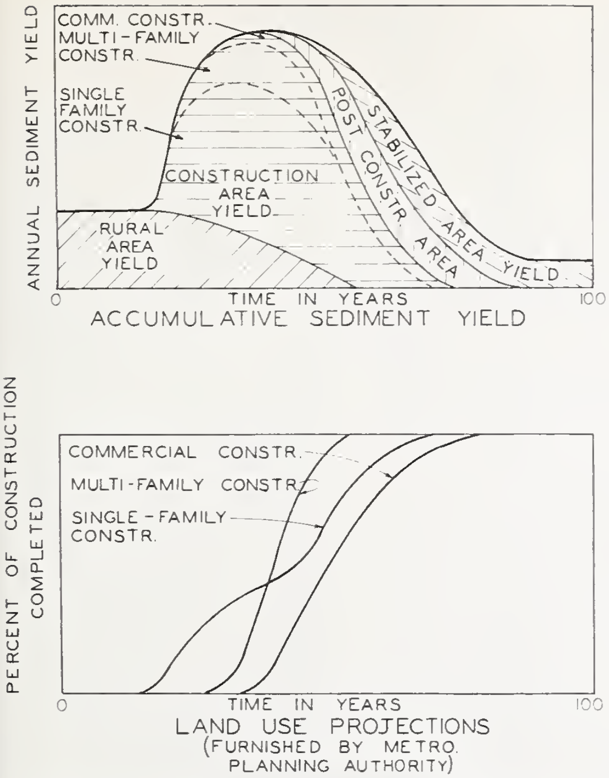

FIGURE 9.—Sediment yields during urban expansion.

ANNUAL SEDIMENT YIELD FROM SOURCE AREAS					
YEAR	RURAL	CONSTRUCTION	POST CONSTR.	STABILIZED	TOTAL
1	X				X
2	X				X
3	X				X
4	X	Y			X+Y
5	X	Y			X+Y
6	X	Y	Z		X+Y+Z
7	X	Y	Z		X+Y+Z
8	X	Y	Z	W	X+Y+Z+W
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
n-8	X	Y	Z	W	X+Y+Z+W
n-7		Y	Z	W	Y+Z+W
n-6		Y	Z	W	Y+Z+W
n-5			Z	W	Z+W
n-4			Z	W	Z+W
n-3			Z	W	Z+W
n-2				W	W
n-1				W	W
n				W	W
TOTAL	ΣX	ΣY	ΣZ	ΣW	$\Sigma(X+Y+Z+W)$

FIGURE 10.—Summation of total sediment yield during conversion from rural to urban land use.

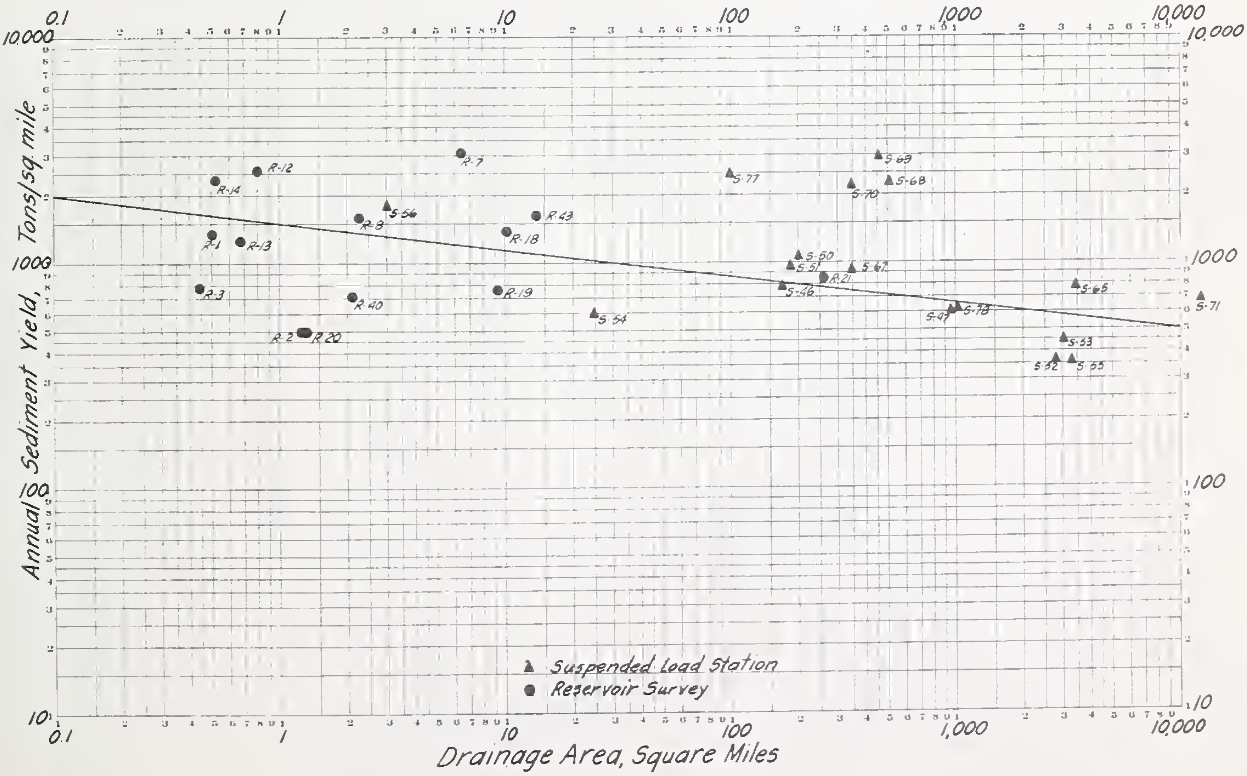

FIGURE 11.—Observed sediment yields, land-resource area 108.

Debris basin			Burn in drainage area		Debris-producing flood		Observed debris production during flood			Debris production factors for—				Correction factors					Computed debris production	
No.	Name	Drainage area	Year	Area	Year	Years after burn	Total	Rate	Observed debris rate adjusted to 100 percent burn 1st year	Slope	Drainage density	Hypsometric index	3-hour rainfall	Slope	Drainage density	Hypsometric index	3-hour rainfall	Total	For maximum 1 square mile with 100 percent burn 1st year[3]	For year of observed flood and actual area burned
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)
		Square miles		*Square miles*			*Cubic yards*	*Cubic yards per square mile*	*Cubic yards per square mile*	*Feet per mile*	*Miles per square mile*		*Inches*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Cubic yards*	*Cubic yards*
	La Cresenta Area:																			
1	Dunsmuir	0.84	1933	0.78	1938	5	58,800	70,000	695,000	1,390	1.7	0.54	2.94	99	97	98	67	64	1,220,000	106,000
2	Eagle-Goss	.61	1933	.46	1938	5	40,900	67,050	767,000	1,480	3.3	.25	2.89	100	84	33	64	18	342,000	19,400
3	Haines	1.53	1933	1.01	1938	5	52,000	33,990	423,000	1,040	2.4	.46	2.85	92	95	98	62	52	1,010,000	117,000
4	Hall-Beckley	.83	1933	.63	1938	5	86,300	103,980	1,185,000	930	2.2	.50	2.82	88	96	100	61	59	990,000	73,000
5	Hay	.20	1933	.06	1938	5	12,600	63,000	1,190,000	1,290	.6	.65	2.72	97	99	76	56	40	760,000	9,700
6	Pickens	1.84	1933	1.75	1938	5	122,200	66,410	650,000	940	3.4	.47	2.93	88	82	99	67	48	910,000	160,000
7	Shields	.27	1933	.24	1938	5	33,500	124,000	1,320,000	1,570	2.5	.51	2.90	100	94	100	65	61	1,160,000	34,400
8	Snover	.23	1933	.11	1938	5	16,800	73,040	1,110,000	1,280	3.5	.54	2.82	97	81	98	61	46	874,000	15,500
	Pasadena Area:																			
9	Fair Oaks	.21	1935	.21	1938	3	12,000	57,140	257,000	1,180	0	.21	2.34	95	100	25	36	9	171,000	9,600
10	Fern	.30	1935	.30	1938	3	20,700	69,000	310,000	1,180	4.8	.41	2.42	95	51	92	39	17	323,000	24,600
11	Las Flores	.45	1935	.31	1938	3	36,000	80,000	495,000	1,610	3.2	.58	2.62	100	85	94	49	39	741,000	60,000
12	Lincoln	.50	1935	.50	1938	3	8,000	16,000	72,000	780	4.6	.31	2.39	81	57	60	38	11	209,000	25,600
13	West Ravine	.25	1935	.24	1938	3	29,800	119,200	555,000	1,290	0	.40	2.40	97	100	90	38	33	627,000	39,500
14	Bailey	.58	1953	.46	1954	1	65,000	112,070	140,000	1,520	2.6	.50	1.70	100	93	100	12	11	209,000	104,000
	Burbank Area:																			
15	Brand	1.03	1927	.77	1943	[4]10	3,100	3,010	99,000	910	3.0	.50	1.70	87	88	100	12	9	171,000	5,300
16	Sunset	.44	1927	.42	1938	[4]10	6,600	15,000	495,000	1,610	2.0	.48	1.93	100	97	99	18	17	323,000	4,800
17	Stough	1.65	[4]	[4]	1943	[4]	33,500	20,300	670,000	1,020	4.4	.62	2.64	91	63	85	52	25	475,000	20,000
	Beverley Hills Area:																			
18	Nichols	.94	[4]	[4]	1938	[4]	17,900	19,040	626,000	480	.9	.56	2.48	57	99	96	42	23	437,000	12,600

[3] 1,900,000 times total percent from column 19.
[4] 10 years or more assumed to have no effect on debris production.

FIGURE 12.Observed data and computed debris production for selected debris basins in the Los Angeles area.

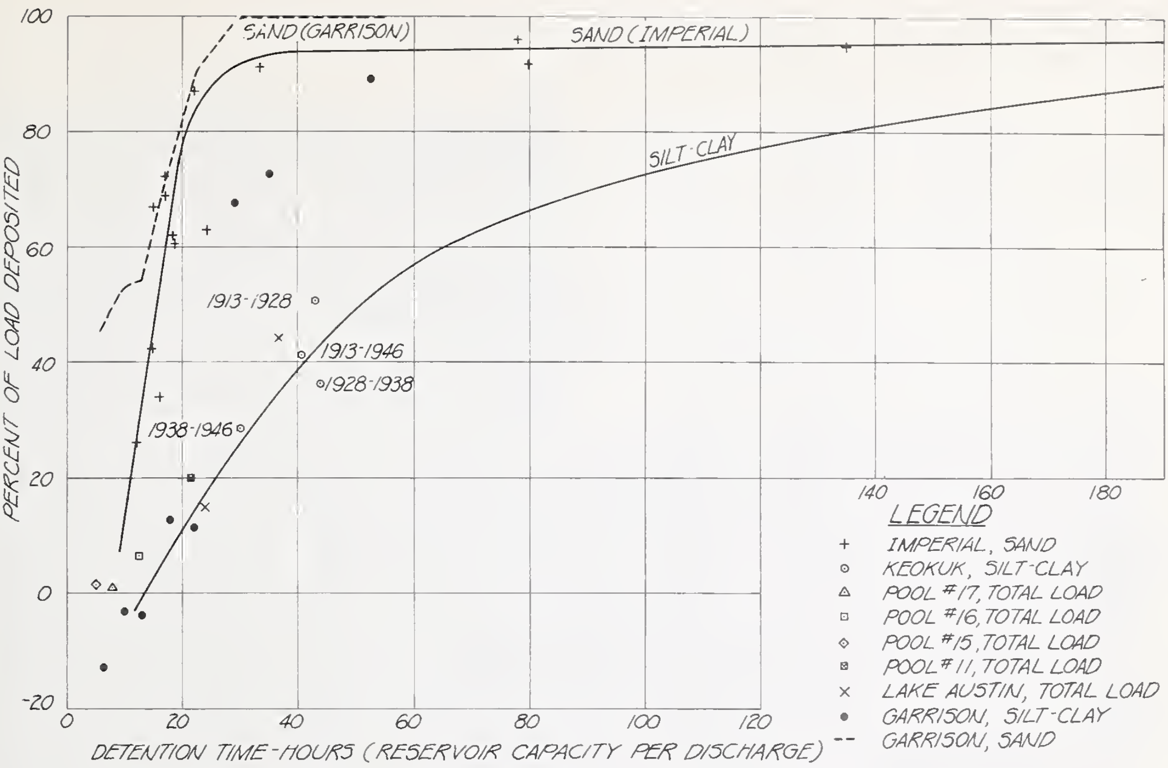

FIGURE 13.—Dardanelle lock and dam. Detention time versus percent of load deposited.

Hydraulic Elements.—This is another method for determining run-of-the-river reservoir yield rates. Individual reservoirs are divided into reaches and hydraulic elements are determined for various discharges by backwater computations. The sediment load is then related to the velocity, depth, and slope, or a combination of such elements. The inflow-outflow sediment loads are computed on a step procedure from reach to reach with backwater computations repeated as necessary to obtain new hydraulic-element values as deposits accumulate with time. The method is time-consuming, but permits recognition of the individual element changes or trends. The reference for this method is the same as given above for the detention-time method.

Bank Caving-Wash Load Yields.—This is another special application method used to estimate the excess rate of bank caving over bank building relative to an increase in the wash load being transported. It applies, again, to run-of-river reservoirs where the erosion of concave banks in bends may continue at the natural high flow rates, due to the duration of artificial bank full stages under operating conditions. The change in the bank caving-bank building equilibrium produces additional wash load from channel widening. The method is admittedly oversimplified for the complex phenomenon of bank caving, but it offers a systematic method of recognizing the increase in wash load attributable to bank caving. An example of this method is given in figures 14 and 15. Reference details can be found in a Supplement to Dardanelle Reservoir Design Memorandum No. 6-4 prepared by the Little Rock District in January 1959.

Sediment-Delivery Ratio.—This category covers both the sediment-delivery and sheet-erosion prediction methods developed by the Department of Agriculture. The application of these methods to Corps projects is generally limited to small watersheds of less than 25 to 50 mi². The Musgrave equation is probably still preferred over the universal soil loss equation for smaller drainages. However, more useful are the various empirical equations developed by such authors as Anderson, Barnes, Brune, Glymph, Gottschalk, Heinemann, Kohler, Maner, Piest, and others. The following sources provide procedural details for these methods: "Studies of Sediment Yields From Watersheds," by Louis Glymph, and "Sediment Sources and Sediment Yields," prepared

WASH LOAD FROM BANK CAVING

Project	Unprotected bank length (miles) x	Wash load portion of bank caving (1,000,000 t/yr./mi.) A_2	Gross wash load from bank caving (1,000,000 t/yr.) A_2x	Natural wash load at projects (1,000,000 t/yr.) A_2/A_1	$A_1x = \frac{A_2x}{A_2/A_1}$	$1-e^{-A_1x}$	Net wash load at lower end of reach from bank caving (1,000,000 t/yr.) L
Years 1 and 2 after closure of Dardanelle							
Keystone to Verdigris River							
Keystone	79	.0209	1.65	18.1	.091	.087	1.57
Total			1.65				1.57
Verdigris River to Webbers Falls							
Keystone	112	.0209	2.34	18.1	.129	.121	2.19
Oologah	60	.0036	.22	2.8	.079	.075	.21
Ft. Gibson	41	.0105	.43	8.5	.051	.049	.42
Total			2.99				2.82
Eufaula to Arkansas River							
Eufaula	27	.0375	1.01	36.2	.028	.027	.98
Total			1.01				.98
Webbers Falls to Van Buren							
Keystone	144	.0209	3.01	18.1	.166	.153	2.77
Oologah	92	.0036	.33	2.8	.118	.111	.31
Ft. Gibson	73	.0105	.77	8.5	.091	.087	.74
Tenkiller	45	.0010	.04	.7	.057	.055	.04
Eufaula	59	.0375	2.21	36.2	.061	.059	2.14
Wister	61	.0007	.04	.5	.080	.076	.04
Total			6.40				6.04
Van Buren to Dardanelle							
Keystone	171	.0209	3.57	18.1	.197	.179	3.24
Oologah	119	.0036	.43	2.8	.154	.142	.40
Ft. Gibson	100	.0105	1.05	8.5	.123	.116	.99
Tenkiller	72	.0010	.07	.7	.100	.095	.07
Eufaula	86	.0375	3.22	36.2	.089	.085	3.08
Wister	88	.0007	.06	.5	.120	.113	.06
Total			8.40				7.34

FIGURE 14.—Wash load from bank caving.

by Robert F. Piest as chapter IV of the American Society of Civil Engineers "Manual on Sedimentation Engineering," and published as paper 7337 in the Journal of the Hydraulics Division, June 1970.

Tailwater Degradation.—Several methods are included in this grouping. Their principle function is to predict degradation trends; but, as part of the computational procedure, sediment-yield values for the degrading reach are developed. Factors considered in their application include composition of the bed material and its coarsening with time, the magnitude of future flows and changes in flow characteristics such as channel shape, depths, velocity, and slope. Three common methods include use of the Einstein bedload function for sediment transport, use of the Kalinske formula to compute bedload plus the development of relationships between natural and modified bed-material load transport as degradation progresses, and determination of the thickness of an armor layer and the depth of scour at which this layer would form. This last technique assumes degradation would cease

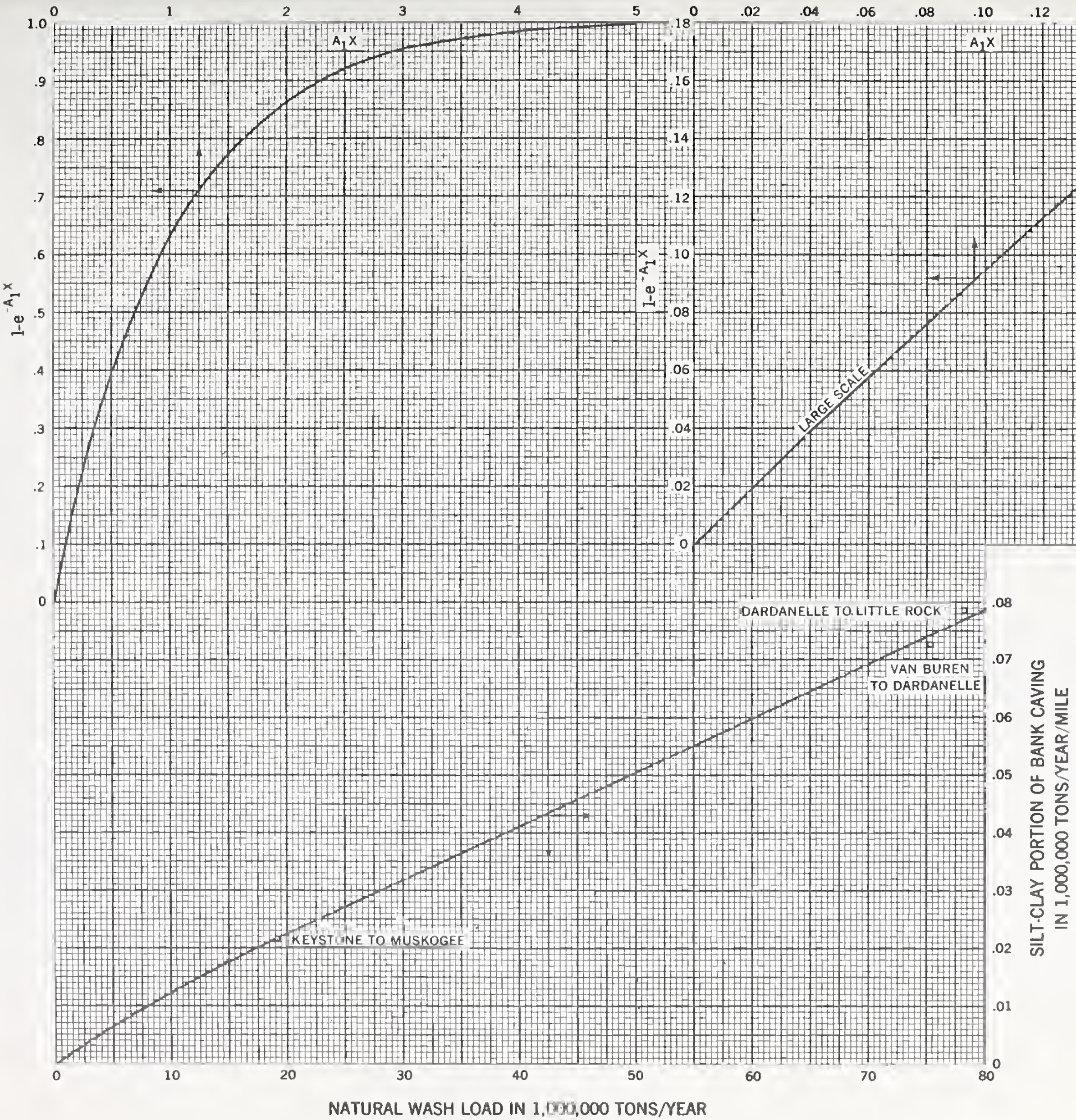

FIGURE 15.—Wash load data from bank caving, Arkansas River.

when a layer of "nonmoving" particles forms a sufficient armor to prevent the effective washing of finer particles from the underlying bed material. Procedural details on these methods can be found in a paper on "Sedimentation Studies for Robert S. Kerr Lock and Dam, Arkansas River Basin," by Howard O. Reese, published in the Hydrologic Engineering Center "Proceedings of a Seminar on Sediment Transport in Rivers and Reservoirs," April 1970.

FUTURE NEEDS

During the past decade a shift in emphasis has taken place within the Corps regarding the need for sediment-yield predictions. Until the mid-1950's, sediment was viewed primarily as a malignant growth that reduced the effectiveness of reservoirs, floodways, navigation channels, and harbors. This was also the period of "big dam" planning and construction, in which sediment depletion rates played a relatively minor role in design because of the voluminous storage allotted for multiple-purpose use. The need for sediment-yield predictions for large drainage areas has essentially vanished. As an indication, about 15 years ago the Corps was operating 135 sediment load stations of which 43 pct had drainage areas greater than 5,000 mi², 27 pct were in the 500–5,000 range, and 30 pct were less than 500 mi². At present the number of stations has doubled, with a shift to a percentage ratio of 25:37:38. Almost half of the active stations are operated for planning or design purposes. For example, during 1969 the Corps had under construction 23 reservoir projects for hydroelectric power and flood control, 64 for flood control and multipurpose use, and 84 local flood-control protection projects. Now, emphasis seems to be focused on projects with sediment-contributing drainages that generally vary within the 500- to 2,500-mi² range. But if our prediction approach is to continue on an empirical basis, long-term data records for drainage areas within this bracket are inadequate, particularly for reservoir survey data. It is estimated that there are some 28,000 reservoirs in the United States, yet we have sediment yield records on only 4 pct. But more significant is the fact that of the 1,200 individual reservoirs listed in the 1965 summary of reservoir survey data, 80 pct of the documented record ranges below 50 mi² and 90 pct below 500 mi². It is apparent that, figuratively speaking, a scarcity of data exists in the no-man's land that is bracketed with voluminous SCS records on the low side and adequate Corps, USBR, and TVA experience on the high side. In essence, the basis for future Corps yield predictions by empirical methods will be somewhat handicapped until data records within this bracket are expanded by measurements or enhanced by correlation techniques.

Today, the dirty word "sediment" has dual connotations; it must now be recognized from both a beneficial and detrimental point of view. On one hand, sediments rank as a major cause of water pollution, but on the other hand, they play a dominating role in water quality control due to their assimilation capabilities. Apparently they also serve similar dual roles as catalytic or transporting agents in physical, chemical, or biological processes. With the current focus of Corps activities in areas of environmental control, urban development or expansion, and waste-water management, the recognition of such aspects is receiving prime attention in planning and design. But unanswered questions continue to outnumber even qualified answers. There is an unquestionable need for further amplification of key sedimentation influences in certain environmental processes before proceeding with detailed planning and design applications.

The immediate needs of the Corps of Engineers in expansion of sediment-yield prediction methods will probably be focused along two major channels—definition of empirical relationships for drainage areas of moderate size, and establishment of the role sediments play in the complex environmental process. Computer-oriented methods for mathematical simulations and modeling will undoubtedly play a key role in the solution of some of these problems. Past experience however, has clearly demonstrated that one or two standard methods or universal equations, regardless of their complexity, will not meet the diverse needs of modern-day engineering, planning, and design. For this reason, we will continue to concentrate our efforts along the lines of practical needs to resolve particular problems. But in doing so, we intend also to continue our policy of improving available methods and techniques, regardless of their degree of sophistication, as the problems warrant.

USE OF EROSION EQUATIONS AND SEDIMENT-DELIVERY RATIOS FOR PREDICTING SEDIMENT YIELD

By Graham W. Renfro[1]

INTRODUCTION

The Soil Conservation Service, under several Congressional authorities, conducts a wide variety of surveys and investigations through watershed protection, flood prevention, and other associated programs. Various types of sedimentation studies are necessary, as part of these investigations, in order to formulate projects and to develop watershed and other project plans. Among the most important of these studies is the development of sediment-yield estimates, for both without-project and with-project conditions. Sediment-yield information is used for many purposes, including determination of sediment damage, allocation of sediment storage in reservoirs and debris basins, development of control measures, and determination of benefits realized by reduction in yields.

GROSS EROSION

In determining average annual sediment yield by use of delivery-ratio curves, the first step is to determine the average annual gross erosion, from all sources, in the watershed area above the point where the yield estimate is needed (such as a proposed floodwater-retarding structure).

Some or all of the types of erosion that may be important in the study of such a watershed are sheet and rill erosion, gully erosion, streambank erosion, flood-plain scour, road and roadside erosion, and erosion from mine wastes, industrial areas and construction sites.

Sheet Erosion

There are several different methods of computing the amount of sheet erosion. These were developed primarily to determine the amount of soil lost from the field (erosion), and consequently they do not express sediment yield without due consideration to the processes of entrainment and transport.

Measurements of soil loss from experimental plots on different soils, slopes, and with different climatic conditions and rainfall patterns under different kinds and combinations of land use were summarized by C. W. Musgrave and associates, Soil Conservation Service, in 1949 (*5*).[2] Measurements were available from 19 research stations and covered periods of from 5 to 15 years. From the study and evaluation of these data, it was determined that the rate of sheet erosion is related to a number of major factors and that certain relationships exist between these factors. An empirical formula was developed:

$$E=F(R/100)\,(S/10)^{1.35}(L/72.6)^{0.35}(P_{30}/1.25)^{1.75},$$

where E=the probable soil loss, in tons per acre per year,

F=a soil factor, based upon the erodibility of the soil and other physical factors,

R=a cover factor, which may be the product of several factors related to the use of the land,

S=the steepness of slope, in percent (with 10 pct as the base),

L=the slope length, in feet (with 72.6 ft as the base),

[1] Geologist, Soil Conservation Service, U.S. Department of Agriculture (deceased).

[2] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this paper.

and P=the rainfall. The amount used is the maximum 30-min rainfall expected in the locality from a 2-yr frequency, in inches.

The above equation, referred to as the Musgrave equation, has been used by the Soil Conservation Service to estimate sheet erosion for several years. The ratios shown for the factors vary for different sections of the United States.

A modification of the Musgrave equation was used by Beer, Farnham, and Heinemann in a study of sediment yields in western Iowa (*1*). A limited use has been made of this equation, which is

$$E=0.59(KR/150)P(R/100)(S/10)^{1.35}(L/72.6)^{0.35},$$

where E=the average annual soil loss, in inches per year,
KR=the product of the soil erodibility factor and the rainfall factor from the universal soil loss equation,
P=the supporting conservation practice factor from the universal equation,
R=the cover factor (fallow or continuous row crop equal 100),
S=the degree of land slope, in percent (with 10 pct as the base),
L=the length of land slope, in feet (with 72.6 ft as the base),
and 150 and 0.59 are constants for annual soil loss in tons and for the cropping factor for continuous row crop (universal) respectively.

Another modification of the Musgrave equation, which has been extensively used by the Soil Conservation Service, substitutes the K and R factors from the universal soil loss equation for the F and P factors of Musgrave. This equation is

$$E=KCR(S/10)^{1.35}(L/72.6)^{0.35},$$

where E=sheet erosion, tons per year,
K=soil erodibility factor,
C=cover factor,
R=rainfall factor,
S=land slope, in percent,
and L=length of slope, in feet.

The universal soil loss equation (*10*) has been used for several years by the SCS in the Conservation Operations Program, where its application was limited to predicting soil loss on cultivated land. It has not been used in watershed studies because factors reflecting the effect of cover on pasture, range, and forest land had not been developed. Cover factors for these land uses have recently been developed, and the equation can now be utilized in watershed, river basin, and resource conservation and development project investigations (*9*).

The universal soil loss equation is

$$A=RKLSCP$$

where A=is the computed soil loss per unit area,
R=the rainfall factor, the number of erosion-index units in a normal year's rain (the erosion index is a measure of the erosive force of specific rainfall),
K=the soil-erodibility factor, the erosion rate per unit of erosion index for a specific soil in cultivated continuous fallow, on a 9-pct slope 72.6 ft long,
L=the slope-length factor, the ratio of soil loss from the field slope length to that from a 72.6-ft length on the same soil type and gradient,
S=the slope-gradient factor, the ratio of soil loss from the field gradient to that from a 9-pct slope,
C=the cropping-management factor, the ratio of soil loss from a field with specified cropping and management to that from the fallow condition on which the factor K is evaluated,
and P=the erosion-control practice factor, the ratio of soil loss with contouring, stripcropping, or terracing to that with straight-row farming, up-and-down slope.

Channel Erosion

Although universally accepted equations for estimating channel erosion have not been developed, there are various ways and means for estimating average annual soil loss from this source. Channel erosion includes gully erosion, streambank erosion, valley trenching, streambed degradation, and flood plain scour. In many water-

sheds these sources are much more significant than sheet erosion as a source of sediment.

In watersheds investigated by SCS there are usually two, and often three, sets of aerial photographs available, with several years between coverages. With these photographs it is often possible to measure channel enlargement from gullies or streambanks and arrive at average annual rates of soil loss.

If only one flight is made, the rate can be determined by ground measurements to the cutting edge of the bank from carefully identified points on the photos and on the ground. The line measured on the ground is a straight line between two identifiable points, one left and one right of the channel. This permits an exact rectification of the photographic scale on this line.

Other Erosion Sources

Soil loss rates from mine wastes, construction activities, roads, gravel pits, and related sources are problems commonly encountered, but with no common solution. Many roads and skid trails can be cross-sectioned and the volume of erosion to date determined. If the history of that stretch of road is known and the extent of the cut involved in construction is determined, the gross amount of erosion, to date, can be determined. Average annual amounts can then be estimated.

Areas involved in housing developments, superhighways, airports, strip mining, and other activities are given independent consideration. The amount of sediment produced is usually estimated by the geologist, in consultation with the others on the planning party, as well as by the engineers in charge of the development. Many of these sources are short lived and have little influence upon a long-range watershed program. On the other hand, many areas are being converted from agricultural to urban use, and the effect of this conversion upon soil loss and sediment yield, as well as hydraulic characteristics of the watershed, must be recognized.

SEDIMENT YIELD

Sediment yield is dependent on gross erosion in the watershed and on the transport of eroded material out of the watershed. Only a part of the materials eroded from upland areas in a watershed is carried out of the watershed. Varying proportions of the eroded materials are deposited as colluvium at the base of slopes and in swales or, as alluvium in natural or artificial lakes, on flood plains and in channels within the watershed. Therefore the magnitude of yield usually varies for different parts of a watershed.

SEDIMENT-DELIVERY RATIOS

The determination of the sediment-delivery ratio is of primary importance to the investigator in order that he may provide realistic estimates of total sediment yield based on computed gross erosion. A characteristic relationship of sediment yield to erosion alone apparently does not exist. Many factors influence the sediment-delivery ratio, and unless all of these factors are uniform from watershed to watershed, the relation of sediment yield to erosion shows considerable variation.

Factors Influencing Sediment-Delivery Ratios

Variations in sediment-delivery ratios are dependent on some or all of the following influences and there may be others not yet identified.

Sediment Source.—The sediment source affects the sediment-delivery ratio. Channel erosion produces sediment that is immediately available to the transport system, and much of it tends to remain in motion as suspended sediment or bedload. Materials derived from sheet erosion, however, often move only short distances and may lodge in areas remote from the transport system. They may remain in the same fields in which they originated or be deposited on more level slopes as colluvium.

Magnitude and Proximity of Sediment Source.—Another factor that will affect the sediment-delivery ratio is the quantity of sediment available from a sediment source and the proximity of the source to streamflow. For example, a large amount of material is available from severe erosion in an area remote from the stream, but its delivery ratio is less than that of a smaller amount of material made available by moderate erosion close to the stream. When the amount of sediment available for transport exceeds the capability of the transporting system, deposition

occurs and the sediment-delivery ratio is decreased.

Transport System.—Runoff resulting from rainfall and snowmelt is the chief agent for transporting eroded material. The ability to transport sediment is dependent on the velocity and volume of water discharge as well as the amount and character of the material supplied to it. The frequency and duration of discharges affect the total volume of sediment transport. The extent and condition of a stream system have considerable bearing on the amount of sediment it can transport. A system with a high channel density has the greatest opportunity to transport eroded materials from the area and should indicate a high sediment-delivery ratio. The condition of the channels—clogged or open, meandering or straight—influences velocity and consequently the delivery ratio. High stream gradients are generally associated with steep slopes and high relief and provide efficient transport of eroded material. The converse is true for low stream gradients.

Texture of Eroded Material.—The texture of the eroded material also influences sediment-delivery ratios. If the eroded material is sand, efficient transport systems and relatively high velocities are necessary to transport it. Much of the eroded material of this type is deposited in the upstream areas when a significant drop in velocity occurs. Usually, it becomes a part of the sediment load only when the source areas are adjacent to an efficient transport system. If the material consists of fine silt and clay, it probably will stay in suspension in continuous flow, and a large portion will be delivered to a downstream point. Some of the coarser particles of the generally fine-grained material may be deposited as colluvium prior to reaching the transport system. Often the larger grain-size materials are made available for transport by channel erosion while the silts and clays are generally made available by sheet erosion.

Depositional Areas.—Sometimes deposition occurs at the foot of upland slopes, along the edges of larger valleys, in valley flats, in and along main stream channels, and at the heads of and in reservoirs, lakes, and ponds. Such deposition within a watershed will decrease the amount of sediment delivered at downstream points.

Watershed Characteristics.—An important characteristic of a watershed is the size of the drainage area; its topography also influences sediment-delivery ratios. The shape of land surface is an inherent feature of the physiographic section in which the watershed is located. Slope is a major factor affecting rates of onsite source erosion. High relief is often indicative of high sediment-delivery ratios. The relief-length ratio (R/L) apparently has a great effect on the sediment-delivery ratio. For use in the R/L ratio, the relief, measured in feet, is defined as the difference in elevation between the average elevation of the watershed divide at the headwaters of the main stem drainage and elevation of the streambed at the point of sediment-yield measurement. Length is defined as the maximum valley length, in feet, measured essentially parallel to the main stem drainage from the point of yield measurement to the watershed divide. The shape of a watershed will affect the sediment-delivery ratio to some degree. Channel density also bears a relationship to the sediment-delivery ratio, but studies to date show that, in any given land-resource area, channel density and topography are closely related.

Procedures for Estimating Sediment-Delivery Ratios

To determine an average sediment-delivery ratio, the magnitude of the sediment yield at a given point in a watershed and the total amount of erosion must be known. Where such information is available, the determination of the sediment-delivery ratio is a simple matter. However, measured data of both required items are not available in most small watersheds.

The gross erosion in a watershed can be estimated with standard SCS procedures. Sediment yield can be determined by reservoir sedimentation surveys or by a program of sediment-load measurements.

Reservoirs frequently are not located at the points where sediment yields are needed, and a program of sediment-load sampling may be a long and expensive procedure. However, if the ratio of known sediment yield and erosion within a homogeneous area can be analyzed in conjunction with some measurable influencing factor, such data can be used to predict or estimate sediment-delivery ratios for similar areas for which measured data are lacking.

In a given physiographic area, finding measurable influencing factors that can be definitely

related to sediment-delivery ratios is the goal of any delivery-ratio analysis. As pointed out in the preceding discussion, there are many factors that may influence sediment-delivery ratios. Some are more pronounced in their effect than others. Some lend themselves to quantitative expression whereas others do not.

An effective means of developing information for use in estimating sediment-delivery ratios is by statistical analysis using the sediment-delivery ratio as a dependent variable and measurable watershed factors as the independent, or controlling, variables. In such an analysis, quantitative data concerning sediment yields, erosion, and measurable watershed factors must be available. Reservoir sedimentation surveys afford a source of sediment-yield data. Erosion information can be developed as previously mentioned, and watershed factors can be determined from available maps or by field surveys. These data can be analyzed to develop a means for estimating sediment-delivery ratios for similar areas.

An analysis of data obtained from several studies is presented in figure 1 (*2, 3, 4, 6, 7*). This general curve is based on data that indicate a wide variation in sediment-delivery ratios for any given drainage area size. This analysis of data from widely scattered areas does, however, show that there evidently is some similarity in the sediment-delivery ratios throughout the country and that, roughly, they vary inversely as the 0.2 power of the drainage area. Estmates of sediment-delivery ratios can be made through the use of figure 1, but any such estimate should be tempered with judgment and consideration of other influencing factors such as texture, relief, type of erosion, the sediment-transport system, and areas of deposition within the drainage area. As an example, when the texture of the upland soils is essentially silt or clay, the sediment-delivery ratio (percent of erosion) may be higher than indicated in figure 1; and when the soil texture is coarse, the sediment-delivery ratio may be lower than shown.

BLACKLAND PRAIRIE STUDY

Somewhat more refined sediment-delivery ratio–drainage area relationships have been developed for individual physiographic areas. One of these is the Blackland Prairie in Texas (*4*). For this study annual sediment yield data were available from 14 watersheds ranging in size from 0.43 to 97.4 mi². Sediment-yield values for the sample watersheds were established by adjusting measured reservoir sediment deposition for reservoir trap efficiency and sediment densities.

Watershed Studies

Annual gross erosion estimates were made separately, computing the amount derived from sheet, channel, and gully eroson. The average annual quantity of material derived from channel and gully erosion was determined by estimating the annual increase in void area (expressed as volume) for all channels and gullies. Annual sheet erosion rates were computed by the Musgrave equation (*5*). Detailed studies were made of the watershed above each reservoir to obtain quantitative data on physical characteristics which were thought to influence downstream delivery of eroded material. The variables studied were watershed area, channel density, mainstem channel length, relief-length ratio, and watershed relief and various combinations of these variables. Values for the variables used in the study are shown in table 1.

Analysis of Data

Regression analyses were used to establish mathematical relationships between the dependent variable, sediment-delivery ratio, and various independent variables selected for testing in this study.

Scatter-diagram plots of sediment-delivery ratio against the various independent variables indicated a definite departure from linearity in most cases. Similar plots on logarithmic paper indicated that the relationship between sediment-delivery ratio and various physical characteristics of the sample watersheds is exponential in form. Therefore, the numerical values of all variables were transformed to logarithms for use in the analyses.

Comparison of the log-log plots indicated watershed area to be a slightly better indicator of sediment-delivery ratio than the other variables tested. A nonlinear correlation between watershed area and sediment-delivery ratio was computed to obtain the regression equation:

$$\log DR = 1.87680 - 0.14191 \log 10A,$$

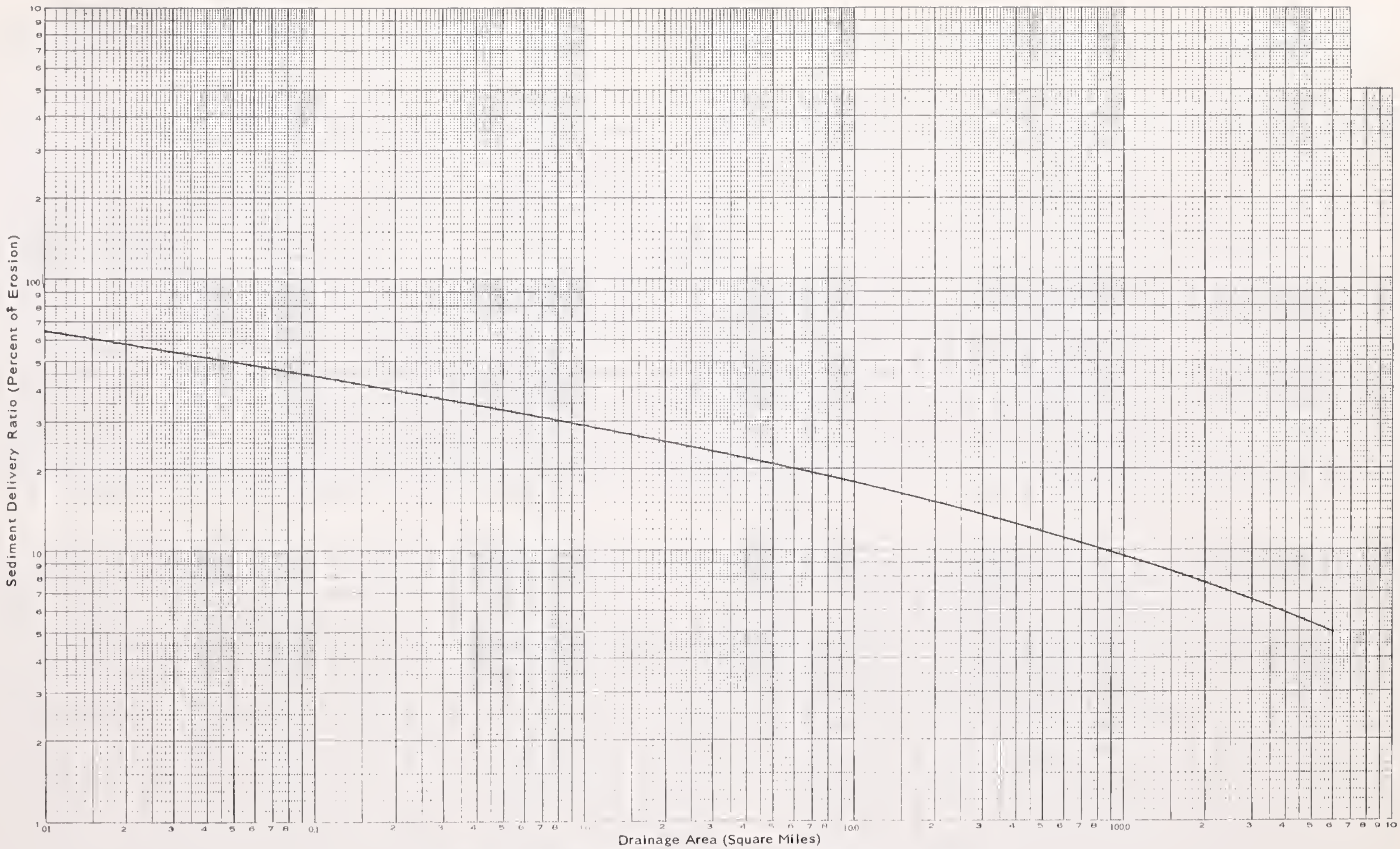

FIGURE 1.—Sediment-delivery ratio versus size of drainage area.

TABLE 1.—*Basic data used in sediment-delivery ratio study, Blackland Prairies, Tex.*

Reservoir	Watershed area[1] (mi²)	Delivery ratio	Relief (ft)	Relief-length ratio	Main-stem length (ft)	Channel length[2] (mi)	Channel density (mi/mi²)
Magnolia Lake	0.43	67	75	0.01420	5,281	1.8	4.18
Rogers Lake	.51	61	100	.01262	7,920	1.5	2.94
Burke Neck Lake	.54	51	46	.00639	7,200	1.6	2.96
Dawson City Lake	1.07	53	60	.00789	7,600	3.4	3.18
Lower Beaton Lake	1.26	54	77	.00898	8,571	2.9	2.30
Floodwater retarding structure No. 12 (Honey Creek)	1.26	53	85	.00805	10,560	3.0	2.38
Lake Gibbons	1.26	52	83	.00898	9,240	4.0	3.17
Floodwater retarding structure No. 11 (Honey Creek)	1.93	52	71	.00806	8,810	5.0	2.59
Ennis City Lake	2.89	47	78	.00591	13,200	5.5	1.90
Floodwater retarding structure No. 4 (Cow Bayou)	5.20	41	150	.00810	18,500	9.0	1.73
Lake Halbert	8.31	42	123	.00388	31,680	14.1	1.70
Terrell City Lake	8.71	38	85	.00310	27,456	12.0	1.38
Lake Crook	49.60	35	163	.00247	66,000	48.0	.97
White Rock Lake	97.40	26	298	.00230	129,560	60.0	.62

[1] Excluding the reservoir area. [2] All channels.

where DR=estimated sediment-delivery ratio, in percent of annual erosion,
and A=sediment-contributing area, in square miles.

The standard error of estimate of this equation is ±0.03007 log units and the coefficient of curvilinear correlation is 0.96, which expresses a 92-pct account of the variations between watersheds in sediment-delivery ratios. The empirical relationship of sediment-delivery ratio to watershed area is presented in the form of the delivery-ratio curve in figure 2.

Subsequent testing of other independent variables, individually and in association with each other, failed to improve the equation shown above. However, channel density (feet of channel per square mile of watershed), relief-length ratio (height of watershed in feet divided by length of watershed in feet, with length measured essentially parallel to the main-stem channel), and main-stem channel length (in feet) were found to be significant indicators of watershed sediment-delivery ratio.

The results of four correlations in terms of correlation coefficient, proportion of explained variation in delivery ratios attributable to each independent variable or combinations of variables, and the relative importance of each correlation in explaining variations in sediment-delivery ratios are presented in table 2.

Characteristics of Watershed Area Variable

A study of the characteristics of the size of watershed variable, when used in a regression analysis with sediment-delivery ratio, showed that the net influence of several watershed factors is represented in the derived equation for estimating sediment-delivery ratio. For example, log-log plots revealed that watershed size is significantly related to the following measurable characteristics of the sample watersheds: (1) Length of all channels: In this relatively homogeneous area, total channel length was found to increase with an increase in size of watershed. (2) Channel density: In contrast to the large watersheds, small watersheds are found to have more linear feet of channel per unit of area. (3) Main-stem channel length: The length of a main-stem channel is directly related to the area of the watershed it serves. (4) Relief: Total relief increases with increasing watershed size. (5) Relief-length ratio: Large watersheds usually have lower relief-length ratio values than smaller watersheds in the same area. (6) Alluvial soils area: In contrast to small watersheds, larger watersheds have a greater proportion of their total area in alluvial soils, indicating an inverse rela-

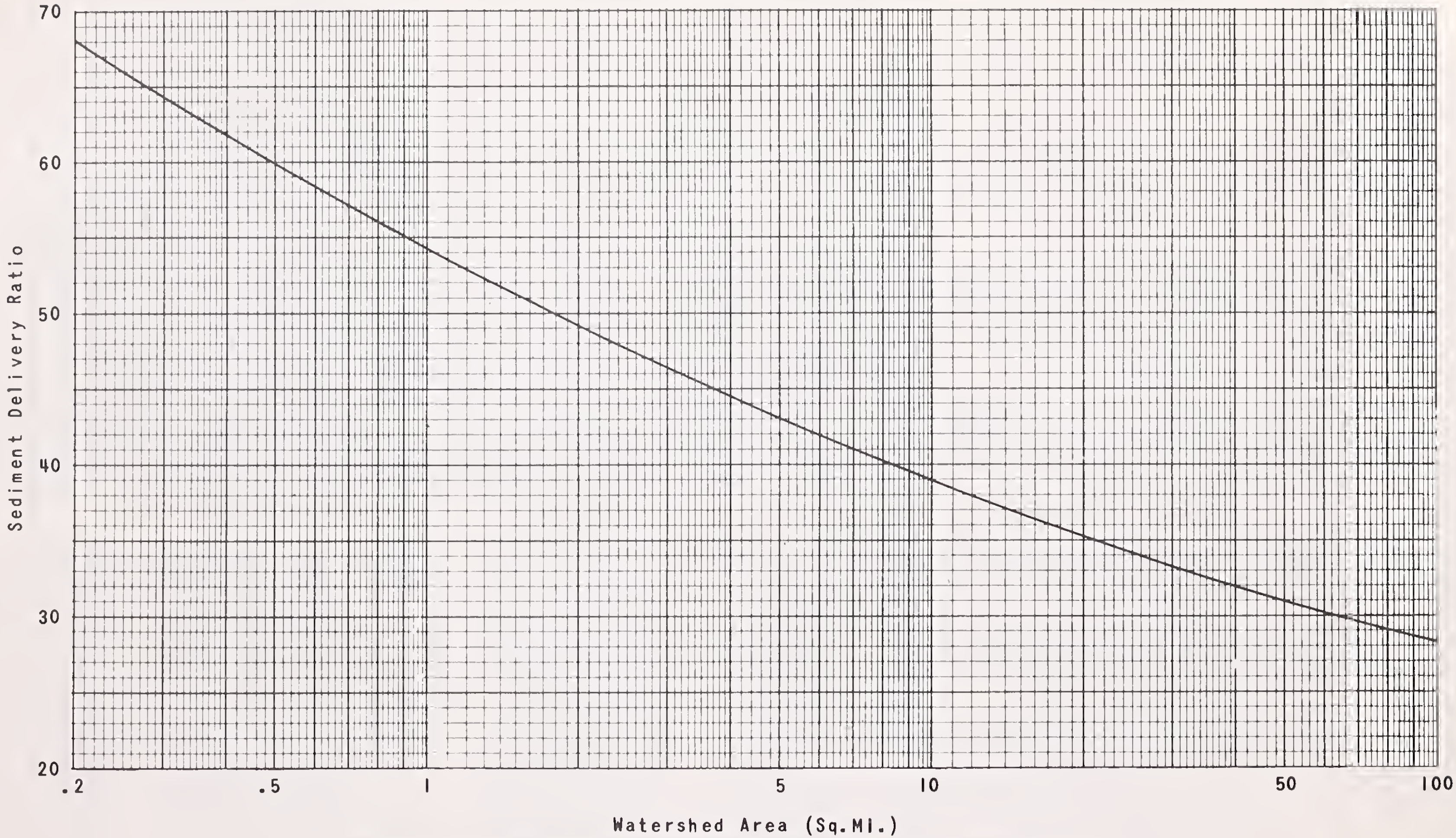

FIGURE 2.—Sediment-delivery ratio curve, Blackland Prairie Land Resource Area.

TABLE 2.—*Results of correlation analyses: Dependent variable, sediment-delivery ratio*

Independent variable	Correlation coefficient R	Proportion of explained variation R^2	Explained variation index
Watershed area ....mi²....	0.96	92	1.00
Channel density ....mi/mi²....	.95	90	.98
Main-stem channel length ....ft....	.94	88	.95
Relief-length ratio	.92	84	.91

tionship between watershed area and downstream delivery of erosional material.

It was concluded that sediment-delivery ratio in the Blackland Prairie Land Resource Area is a function of several watershed characteristics. These are related to and apparently are adequately expressed by the watershed area variable.

RED HILLS STUDY

Another study led to the development of a sediment-delivery ratio curve for the Red Hills physiographic area in Oklahoma and Texas (*3*). This area is also referred to as the Rolling Red Plains Land Resource Area by SCS.

Analysis of Data

This method was developed from results of statistical analyses of 25 records of watershed sediment-delivery rates and factors affecting sediment-delivery rates in the Rolling Red Plains Land Resource Area and is based on the curvilinear relationship between relief-length (R/L) ratio and sediment-delivery ratio. The delivery-ratio curve (fig. 3) was computed from the curvilinear regression equation

$$\log DRe = 2.94259 - 0.82362 \text{ colog } (R/L) \text{ ratio},$$

where DRe=estimated sediment-delivery rate, in percent of annual gross erosion,

and R/L=relief-length ratio.

The standard error of estimate for the equation is ± 0.04041 log units, and the coefficient of curvilinear correlation is 0.987, indicating a highly significant correlation between these two variables.

Relief-Length Ratio Computation

The relief-length ratio is computed by the following procedure. Measure maximum length of the watershed, essentially parallel to the main-stem drainage, from the damsite to the watershed divide. If more than one main drain empties directly into the reservoir, measure the length of each drain and use the average as length of the watershed. From U.S. Geological Survey topographic maps or other topographic information estimate the watershed relief, defined as the difference in feet between the elevation of the watershed divide at the headwaters of the main stem or stems and streambed elevation at the damsite. Divide watershed relief by the maximum length of watershed, in feet, to determine the relief-length ratio.

To determine the watershed sediment-delivery ratio, enter figure 3 with the computed relief-length ratio and read the sediment-delivery ratio in percent of annual gross erosion.

USE OF UNIVERSAL EQUATION AND DELIVERY RATIOS IN WATERSHED PLANNING

Assume a watershed area of 600 acres above a proposed flood-water-retarding structure in Fountain County, Ind. (See fig. 4.) Compute the average annual soil loss from sheet erosion for present conditions and for future conditions after recommended land treatment is applied on all land in the watershed (*8*).

Present Conditions

Cropland, 280 acres
- Continuous corn with residue removed, average yield 70 bu/acre
- Cultivated up and down slope
- Soil, Fayette silt loam
- Slope, 8 pct

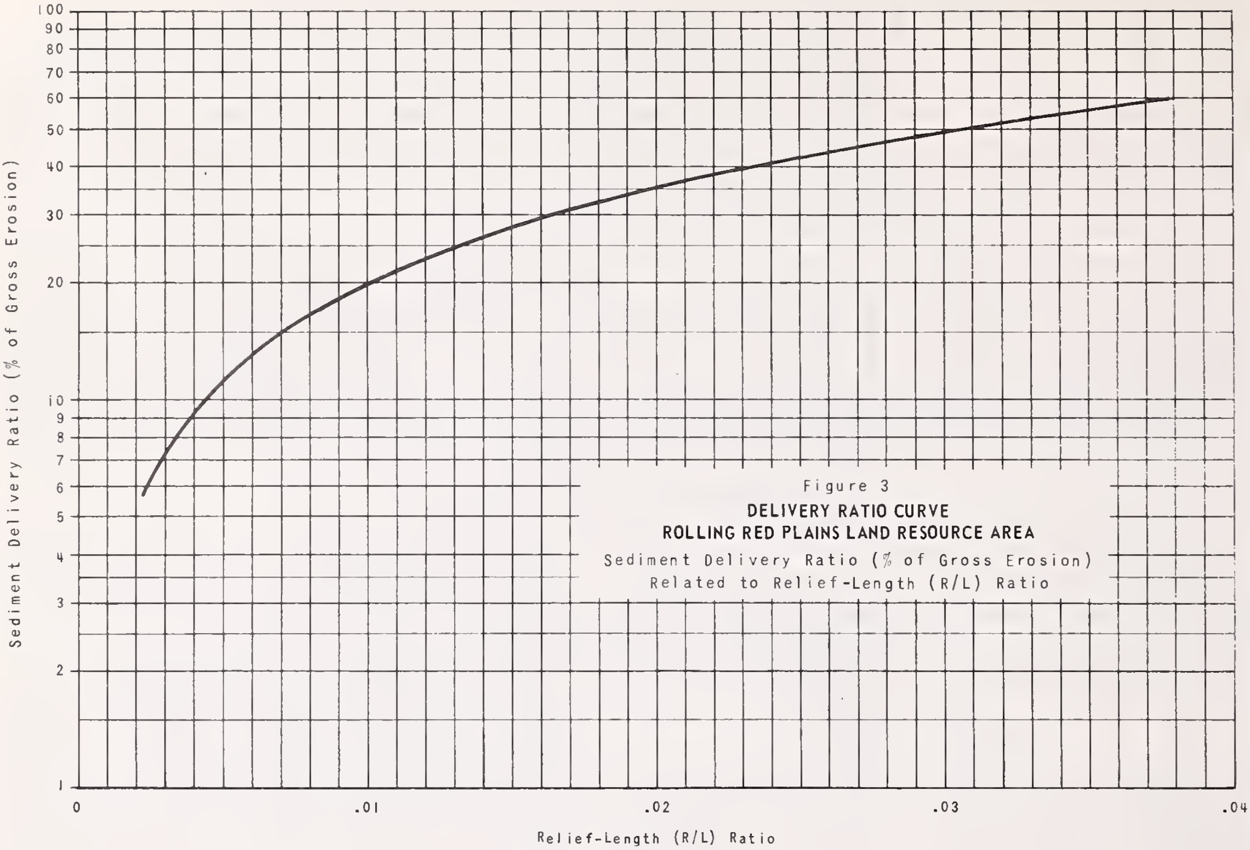

Figure 3
DELIVERY RATIO CURVE
ROLLING RED PLAINS LAND RESOURCE AREA
Sediment Delivery Ratio (% of Gross Erosion)
Related to Relief-Length (R/L) Ratio

Slope length, 200 ft
$R=185$
$K=0.37$
$LS=1.41$
$C=0.43$
$P=1.00$

$$A=185\times0.37\times1.41\times0.43\times1.0=41.5 \text{ tons/acre/yr soil loss}$$

Pasture, 170 acres
Canopy of short brush, 0.5-m fall height
Percent cover provided by canopy, 50 pct
Surface cover, grass and grasslike plants
Percent of surface or ground cover, 80 pct
Soil, Fayette silt loam
Slope, 8 pct
Slope length, 200 ft
$R=185$
$K=0.37$
$LS=1.41$
$C=0.012$

$$A=185\times0.37\times1.41\times0.012=1.16 \text{ tons/acre/yr}$$

Forest, 150 acres
Poorly stocked
Percent of area covered by tree canopy, 30 pct
Percent of area covered by litter, 50 pct
Undergrowth, unmanaged
Soil, Bates silt loam
Slope, 12 pct
Slope length, 100 ft
$R=185$
$K=0.32$
$LS=1.8$
$C=0.05$

$$A=185\times0.32\times1.8\times0.05=5.3 \text{ tons/acre/yr}$$

Future Conditions

Cropland, 280 acres
Rotation of wheat, meadow, corn, corn with residue left
Contour stripcropped
Soil, Fayette silt loam
Slope, 8 pct

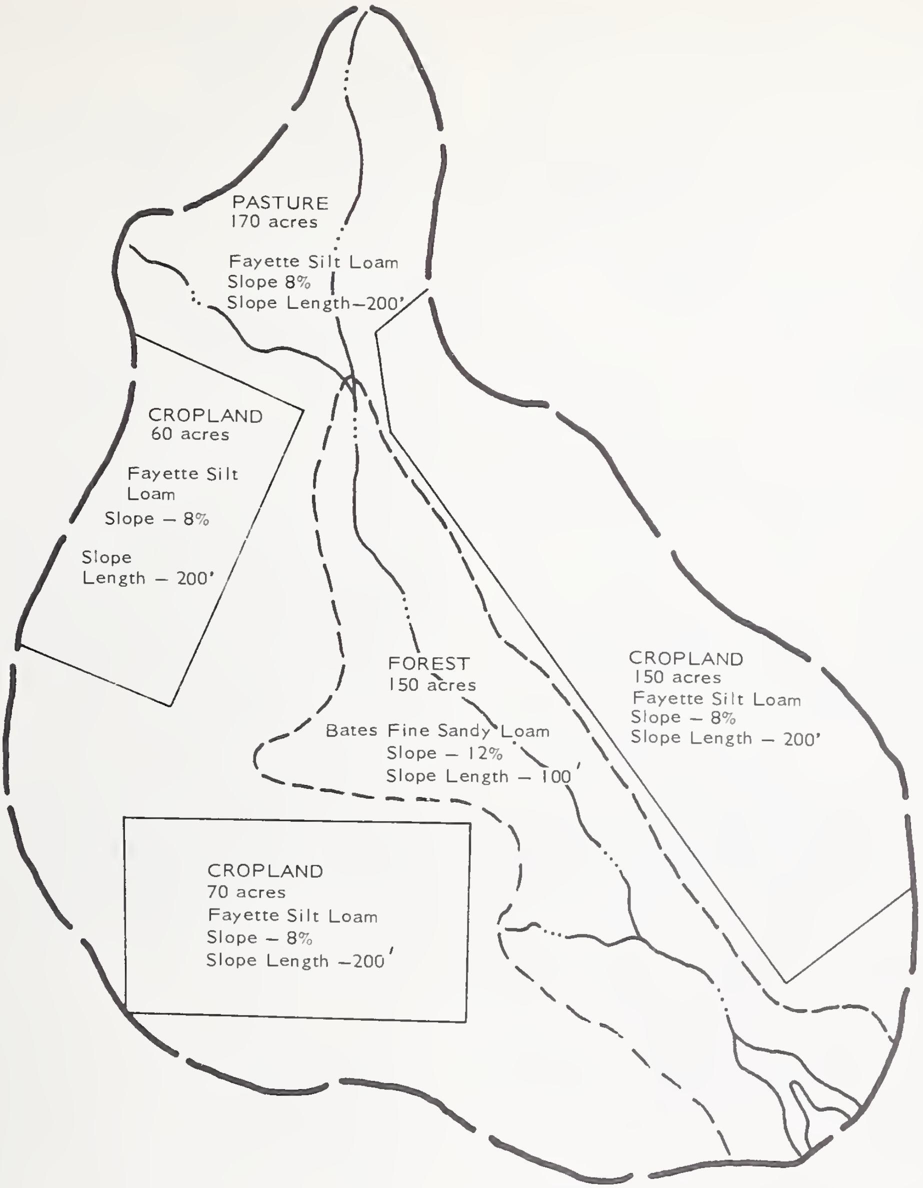

FIGURE 4.—A hypothetical 600-acre watershed for use in example.

Slope length, 200 ft

R=185
K=0.37
LS=1.41
C=0.119
P=0.3

$A = 185 \times 0.37 \times 1.41 \times 0.119 \times 0.3 = 3.4$ tons/acre/yr

Pasture, 170 acres, with improved management
- Canopy cover increased to 75 pct with 0.4-m fall height
- Ground cover increased to 95 pct (for area not protected by canopy)
- Soil, Fayette silt loam
- Slope, 8 pct
- Slope length, 200 ft

$R=185$
$K=0.37$
$LS=1.41$
$C=0.003$

$$A=185\times0.37\times1.41\times0.003=0.29 \text{ tons/acre/yr}$$

Forest, 150 acres, with improved measurement

Medium stocked

Canopy cover increased to 60 pct

Litter cover increased to 80 pct

Undergrowth, managed

Soil, Bates silt loam

Slope, 12 pct

Slope length, 100 ft

$R=185$
$K=0.32$
$LS=1.8$
$C=0.003$

$$A=185\times0.32\times1.8\times0.003=0.32 \text{ tons/acre/yr}$$

Summary of Average Annual Soil Losses

Present Conditions

	Tons/yr
Cropland—280 acres×41.5 tons/acre=	11,620
Pasture —170 acres×1.16 tons/acre=	197
Forest —150 acres×5.3 tons/acre=	795
Total	12,612

Future Conditions

Cropland—280 acres×3.4 tons/acre=	952
Pasture —170 acres×0.29 tons/acre=	49
Forest —150 acres×0.32 tons/acre=	48
Total	1,049

The above summary shows that the total soil loss from sheet erosion under present conditions is 12,612 tons. Assuming that soil loss from other sources is negligible, this represents the total average annual gross erosion in the watershed.

SEDIMENT-DELIVERY RATIOS

Composite Curve

If a sediment-delivery ratio curve for the Indiana and Ohio Till Plain Area, where this watershed is located, has not been developed, the composite curve shown in figure 1 is used. The size of the drainage area is 600 acres or 0.9375 mi^2. Using 0.94, the sediment-delivery ratio is 29 pct and the average annual sediment yield, for present or without project conditions, to the proposed structure is 12,612×0.29, or 3,657 tons.

Blackland Prairie Curve

If a watershed of this size is located in the Blackland Prairie Land Resource Area in Texas, then the sediment-delivery ratio curve developed for this area is used (fig. 2). This curve indicates a delivery ratio of 59 pct.

It is thought that the principal reason for the high sediment-delivery ratios in the Blacklands is the fine texture of the soils. These are almost entirely clays and silty clays which, once detached and entrained, have a high rate of transport as suspended sediment.

Rolling Red Plains Curve

For this size of watershed within the Rolling Red Plains Land Resource Area, the relief-length ratio relationship is used. The approximate total length of the watershed, measured essentially parallel to the main stream, is 8,580 ft. The total relief in the watershed is 190 ft. The relief-length ratio then is 190/8580, or 0.022. Using the curve shown in figure 3, a sediment-delivery ratio of 38 pct is indicated.

SUMMARY

In many instances, measured basic data upon which to base detailed analyses for establishing sediment-delivery ratios are insufficient or entirely lacking. The validity of using an equation for developing sediment-delivery ratios beyond the physiographic area for which it was developed is questionable and generally not recommended. Yet a knowledge of sediment-delivery ratios is needed by investigators to determine sediment yields, to ascertain the relative importance of various sediment sources, and to recommend measures to reduce sediment yields.

Most areas in the country do have information concerning the total sediment yield from some watersheds. Such data are available from suspended-load records and reservoir sedimentation-survey records. Comparing sediment yield and calculated gross erosion gives indications of an expected sediment-delivery ratio for the area. Such an analysis is much less precise than detailed studies, but can be useful where no other data are available.

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THE USE OF SUSPENDED-SEDIMENT LOAD MEASUREMENTS AND EQUATIONS FOR EVALUATION OF SEDIMENT YIELD IN THE WEST

By Elliott M. Flaxman[1]

INTRODUCTION

This paper describes some sediment-yield evaluations that depart from the customary treatment of suspended-sediment load data. The conventional means of securing sediment yield is by summation of long-time records and use of the flow-duration, sediment-rating curve procedure to extend short-time sediment-load records. The latter procedure is frequently used because the suspended-sediment load data are for a much shorter period than the streamflow records.

In determining the suspended-sediment load in tons, the discharge is multiplied by sediment concentration and a conversion factor as given by Porterfield.[2] In this computation, the direct relationship between discharge and sediment concentration is obscured because the computation of tons has already included the discharge value in the determination. The question for which an answer is being sought is whether relating discharge to concentration may aid in solving some of the sediment-yield problems in the Western States. Among these are a concern as to the relative contribution of stream channels compared to the upland sources of sediment. Erosion of the bed and banks of channels is common in arid and semiarid areas and can be an important contributor of sediment. The possibility of interpreting discharge-sediment concentration relationships for this purpose is explored.

In many areas it is difficult to determine what portion of the sediment yield is geologic erosion and what portion is accelerated erosion, usually attributable to man's activities. Discharge-sediment concentration relationships are considered for this purpose.

METHODS OF ANALYZING SUSPENDED-SEDIMENT LOAD DATA

The procedure described involves the random selection of discharge data and suspended-sediment load data from U.S. Geological Survey records. It was decided to use as wide a range of discharge measurements as was available. The amount of data used was limited to the number of observations that could reasonably be duplicated by short-term monitoring. The number of discharge-sediment concentration measurements varied from 25 to 70 and averaged about 40.

Plotting discharge-sedment concentration measurements from a number of stations on log-log paper indicated that a straight line adequately described the general relationship through the range of discharges responsible for the largest percentage of sediment volume at a station. The more complex relationship found at several stations will be described later.

A simple regression analysis was made of the data, and the derived equations are of the form

$$Y=aX^m, \tag{1}$$

where Y=the sediment concentration, in milligrams per liter,
a=a constant,
X=discharge, in cubic feet per second,
and m=an exponent.

[1] Sedimentation specialist, Engineering and Watershed Planning Unit, Regional Technical Service Center, Soil Conservation Service, U.S. Department of Agriculture, Portland, Oreg. 97209.

[2] Porterfield, George. 1972. Computation of fluvial-sediment discharge. Book 3, Chapter C3, Techniques of Water Resources Investigations of the United States Geological Survey, 65 pp.

Whether or not the procedure reasonably reflects actual measurements was examined. This was done by computing the sediment load in tons per year with the derived simple regression equations and comparing this computed load with measured amounts. In most instances, data from years other than those included in developing the equation were used in making this comparison. The measured versus computed suspended-sediment loads shown in figure 1 generally indicate that the equations provide a satisfactory relationship for the described purposes.

In the early stages of the data analysis, discharge-sediment concentration measurements were plotted for a substantial number of gaging stations. It was noted that values for the intercept a tended to increase when the data were from the drier parts of the West and decrease when they were from more humid areas. Sediment concentrations in a given discharge increased in the same manner. This is interpreted as expressing the effect of better vegetation cover and lower concentrations for higher runoff areas and sparse vegetation and higher concentrations for the more arid areas.

Observations of the plotted data coupled with some knowledge of the contributing watersheds indicated that there is a tendency for sediment concentration to increase in approximately direct proportion to discharge in watersheds characterized here as having a "uniform" response to rainfall runoff. A uniform watershed

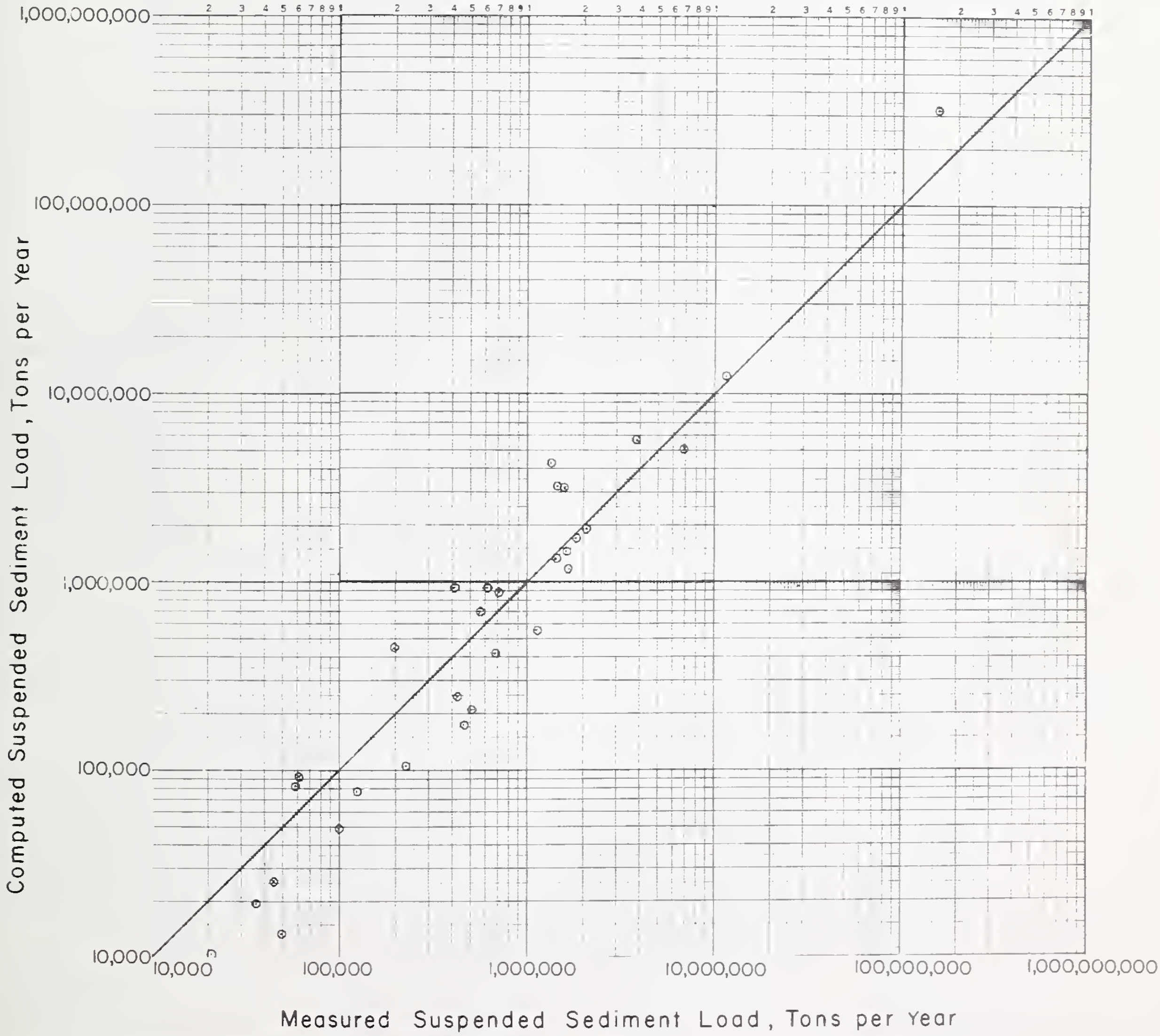

FIGURE 1.—Measured suspended-sediment load compared to computed suspended-sediment load.

is defined here as one for which upland sheet erosion is the dominant source of sediment, and this is yielded to streamflow at a more or less uniform rate over the whole area. The condition described is most likely to be a watershed in a relatively natural condition, although it may be in deteriorated condition, exposing soils over most of the watershed that are equally susceptible to erosion.

In watersheds where sediment concentrations increase in about direct proportion to the increase in discharge, the exponent m has a value of 1.0 or perhaps up to 1.10 as a result of the increased stress on the watershed by infrequent and intense storms. Other observations of plotted data and knowledge of watershed conditions indicate that uniform watersheds with runoff largely due to snowmelt have m values of 1.4 to 1.5. Such large exponents are indicative of very low sediment concentrations during low or moderate discharges relative to the concentrations at higher discharges.

Variable watersheds, as distinct from uniform watersheds, are placed in two classes. These are (1) variable $m<1$ and (2) variable $m>1$. Watersheds in class 1 are those in which sediment concentrations are increasing at a rate less than the proportionate increase in discharge; those in class 2 are those in which sediment concentration is increasing at a greater than proportionate rate of increase in discharge. The class 1 type is characterized by the greater availability of sediment during low and moderate discharges. The sources could be the channel, gullies, or exposed slopes where erosion may readily occur during low-intensity storms or during the early and late stages of a large storm. Class 2 types, other than those described as resulting from snowmelt erosion, are characterized by greater susceptibility to erosion during periods of severe climatic stress in the watershed. Exponents higher than 1.5 have been identified in class 2 watersheds.

In the data studied, values of m less than 1.0 range as low as 0.16. The m of 0.16 is from the San Simon Wash in southeastern Arizona, widely known for the valley trenching extending through its alluvial valley. The Rio Puerco in northwestern New Mexico is an even more notable example of valley trenching because of the hundreds of miles of stream reach involved. The value of m is 0.25. These are average values for a considerable scatter of data that reflect an almost independent relationship between discharge and sediment concentration. In fact, low flows may have sediment concentrations as high as large flows or higher, indicative of the unlimited supply of sediment in streambeds and channel banks, no matter in what portion of the watershed a storm occurs. The volume of sediment from the channel or from lower watershed accelerated erosion apparently does not have to be large to cause the value of m to be less than 1.0, just that concentrations during the lower or moderate flows are proportionately high enough to create an imbalance over so-called uniform conditions.

It was stated above that the value for intercept a tended to increase with increasing aridity of the climate. It is apparent, given the same climatic conditions, that the intercept would be larger as the slope of the curve defined by exponent m becomes steeper. The intercept could also be larger than indicated by the climatic factor if the vegetative cover was poor and other upland watershed conditions were conducive to severe erosion. The effect of these conditions is illustrated in figure 2. The figure shows that several streams are out of place in the sequence of declining a intercepts as average annual runoff decreases. For example, runoff in Flatwillow Creek in Montana, stream 5, is chiefly from snowmelt, and its position to the left of a normal sequence on the graph is indicative of lower erosion in the upland watershed. Stream 6 is Colma Creek in South San Francisco, Calif. The accelerated erosion caused by urban and suburban development has been discussed by J. M. Knott.[3] Stream 7 is the Paria River, which carries the highest sediment concentrations on record in the United States. Exceptionally heavy geologic erosion is widespread in this watershed.

Considering the apparent relationships among average annual runoff, intercept a, and exponent m, a multiple regression analysis was made with average annual runoff and the value of m as independent variables and intercept a as the dependent variable using 32 examples from various parts of the West:

[3] Knott, J. M. 1969. Interim report on streamflow and sediment discharge in the Colma Creek Basin, California. Open File Report, Water Resources Division, U.S. Geological Survey, Menlo Park, Calif., 24 pp.

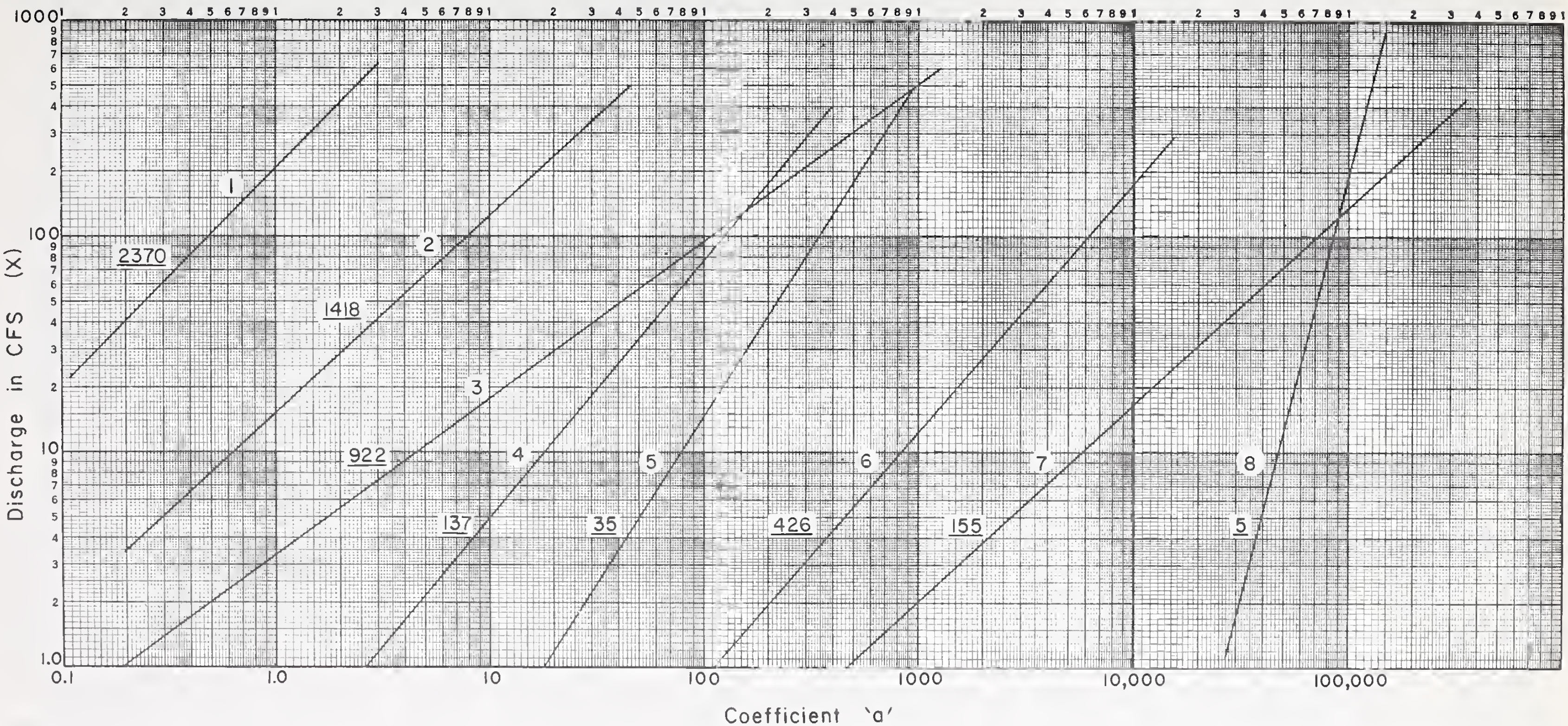

FIGURE 2.—Relationships of discharge to coefficient a in the equation Y (sediment concentration) $=aX^m$. The underlined numbers refer to average annual runoff in acre-feet per square mile. Numbers are keyed to the following watersheds: (1) Chehalis River, Wash.; (2) South Fork Trinity River, Calif.; (3) Waikele Stream, Oahu, Hawaii; (4) Alameda Creek, Niles, Calif.; (5) Flatwillow Creek, near Mosby, Mont.; (6) Colma Creek, South San Francisco, Calif.; (7) Paria River, Lees Ferry, Ariz.; (8) Rio Puerco, near Bernardo, N. Mex.

$$a = \text{antilog } (5.9085 - 1.4964 \log X_1 - 2.2386 X_2), \quad (2)$$

where a=the intercept in equation 1,
X_1=average annual runoff, in acre-feet per square mile,
and X_2=exponent m in equation 1.

The value of r is 0.89, indicating that 79 pct of the variation in a is explained by this equation. The value of t for X_1 is —6.24; for X_2 it is —4.03, both highly significant. The F-ratio is 54, also highly significant.

As a practical application of the interpretation described above, data from San Ramon Creek in Contra Costa County, Calif., is used as an example. Stabilization of the channel banks and streambed was a major element of a pilot watershed program in which the Soil Conservation Service participated with local sponsoring agencies in the mid-1950's. In developing the project work plan, the rate of land loss between 1939 and 1950 along San Ramon Creek was obtained from comparative aerial photography. The average loss was determined to be about 1.55 surface acres/yr. The height of the banks was 10 to 20 ft. As part of a project evaluation, suspended-sediment load samples were obtained on San Ramon Creek at Walnut Creek gaging station between 1955 and 1958, during the early years of project installation. Figure 3 shows the discharge-sediment concentration curve (solid line) approximated from the measurements and a curve (dash line) with an intercept of 2.73 for discharge (Q), computed from equation 2, with m equal to 1.0. This assumes that a value of 1.0 would be appropriate under natural conditions, with no significant channel erosion.

By use of the curves in figure 3 and flow-duration data for San Ramon Creek, it was determined that the average annual sediment yield under 1955–58 conditions was about 60,000 tons, or 1,180 tons/mi^2. The yield without channel erosion would amount to about 25,000 tons/yr, a difference of 35,000 tons between the two conditions. Assuming a weight of 80 lb/ft^3, the volume of sediment from channel erosion is about 20 acre-feet annually, and the upland yield is 0.3 acre-foot/mi^2. The approximations compare favorably with the measurements of channel erosion and of watershed sedimentation rates.

Figure 4 concerns Colma Creek in South San Francisco, Calif. Curve 1 indicates the general trend of a discharge-sediment concentration relationship derived from measurements. Curve 2 is a possible undisturbed watershed relationship, with the intercept of 0.545 determined from equation 2 and with m again equal to 1.0. The very large difference shown here is attributable to urbanization, which has increased the concentration of sediment for a given discharge by a hundredfold. This increase does not include sediment intercepted by debris basins as identified by Knott, cited in footnote 3.

A different example, one of upland watershed slope erosion, is cited in the case of the Waikele Stream, tributary to Pearl Harbor on the island of Oahu, Hawaii. In recent years, the watershed has been undergoing a large amount of urban development; in addition sugarcane and pineapple have been grown for a number of years. Figure 5 shows an approximate relationship between discharge and suspended-sediment concentration developed from a relatively few samples (curve 1). Exponent m has a value of 1.36. Curve 2 is a theoretical curve developed from equation 2 and the assumption that the exponent of 1.10 was indicative of undisturbed conditions. This value is suggested by plotting data from a much less disturbed watershed on the island. Computations from 1 year's flow indicate the sediment yield under the natural vegetation of these tropical surroundings to be only about 12 pct of the present yield. This is assuming that the runoff is approximately the same under both watershed conditions.

The indicated relatively high m of 1.36 for the Waikele Stream may in part be due to the high infiltration capacity of the soil. This could result in low-concentration flows from subsurface sources at lower discharges. Similarly, watersheds with soils of low infiltration capacity could have low m values, in part because of surface runoff during early stages of a storm.

While a straight-line relation between discharge and suspended-sediment concentration appears to be appropriate in accounting for most of the variation, it is by no means always the case. Even in instances where it is true, the lower range of relationships are apt to be curvilinear as indicated in figure 3, curve 1.

Among the most complex of discharge and suspended-sediment concentration relationships existing in the West are those occurring in the wheat-growing country of eastern Washington

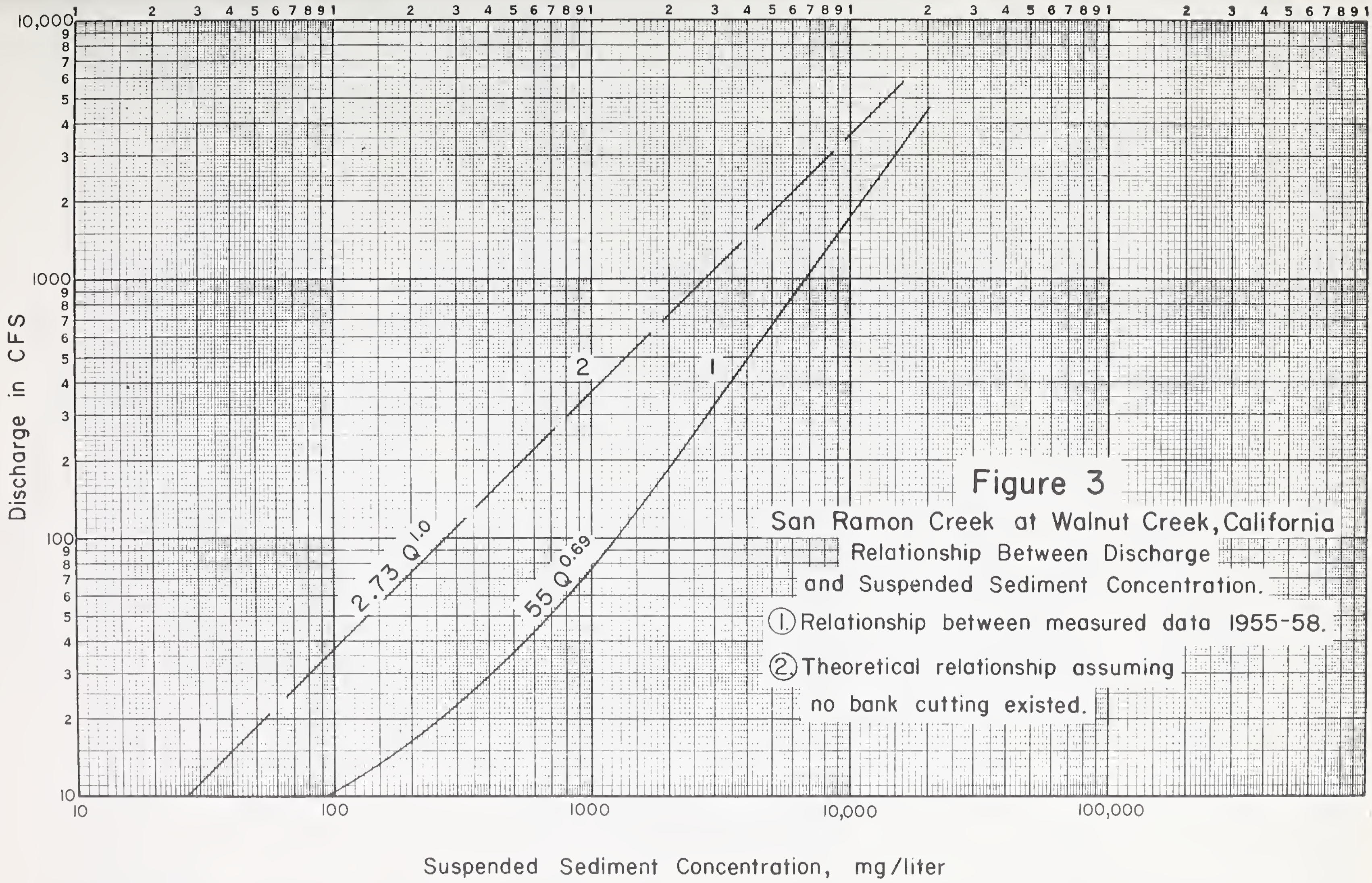

Figure 3

San Ramon Creek at Walnut Creek, California
Relationship Between Discharge
and Suspended Sediment Concentration.

(1.) Relationship between measured data 1955-58.

(2.) Theoretical relationship assuming
no bank cutting existed.

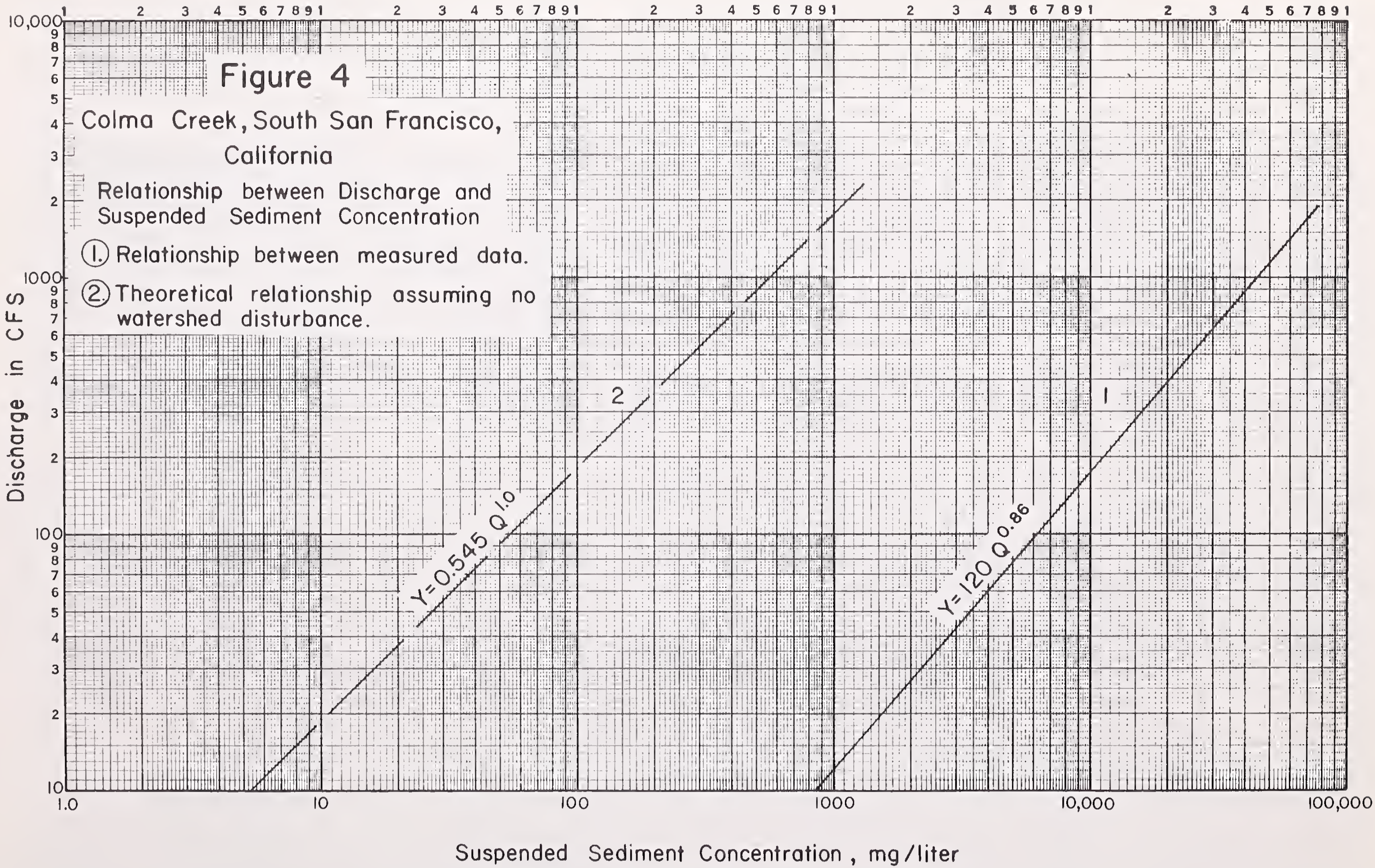
Figure 4
Colma Creek, South San Francisco, California
Relationship between Discharge and Suspended Sediment Concentration
(1.) Relationship between measured data.
(2.) Theoretical relationship assuming no watershed disturbance.
Y=0.545 Q 1.0
Y=120 Q 0.86
1
2
Discharge in CFS
Suspended Sediment Concentration, mg/liter
10
100
1000
10,000
1.0
100,000

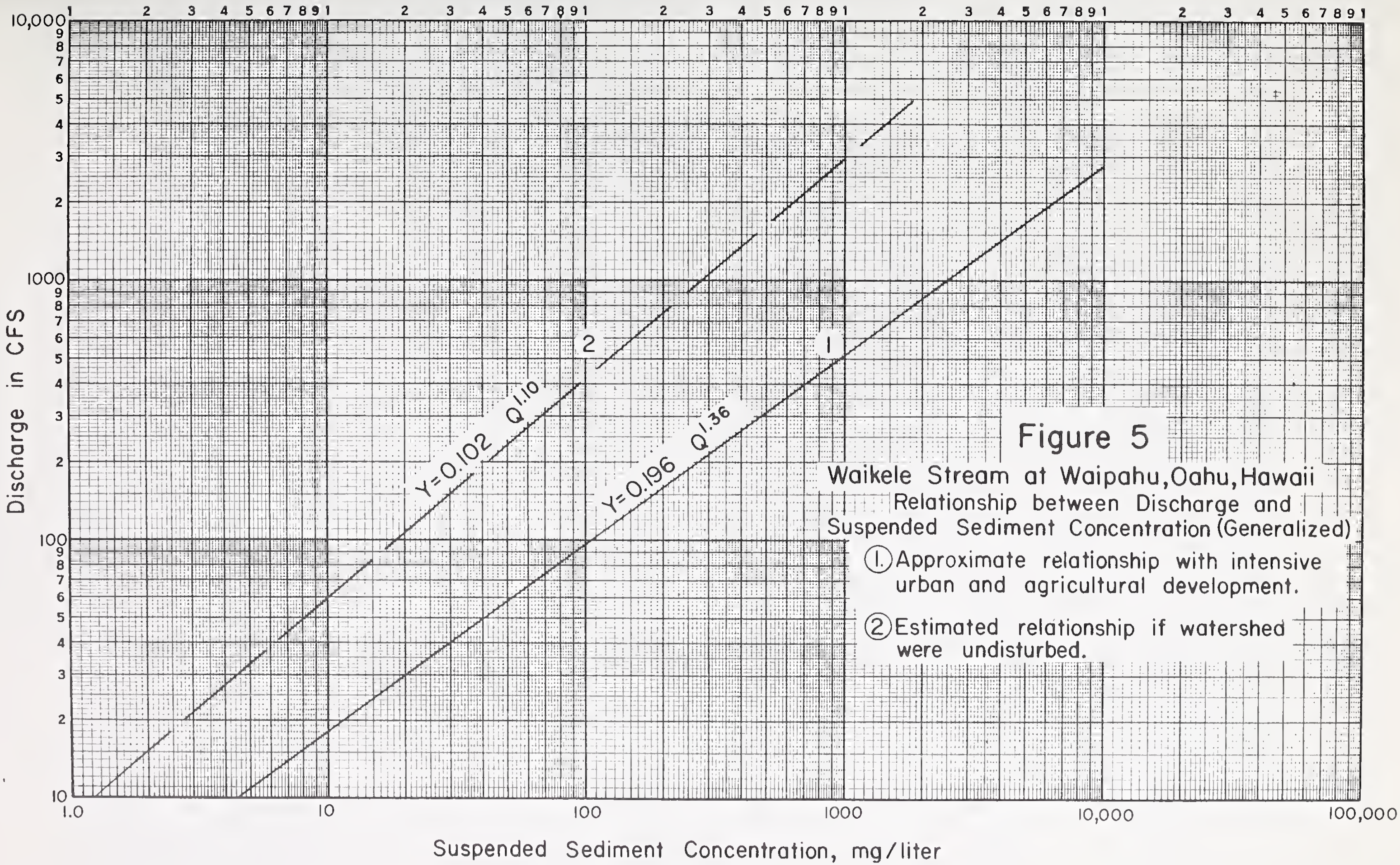

Figure 5

Waikele Stream at Waipahu, Oahu, Hawaii
Relationship between Discharge and Suspended Sediment Concentration (Generalized)

1. Approximate relationship with intensive urban and agricultural development.

2. Estimated relationship if watershed were undisturbed.

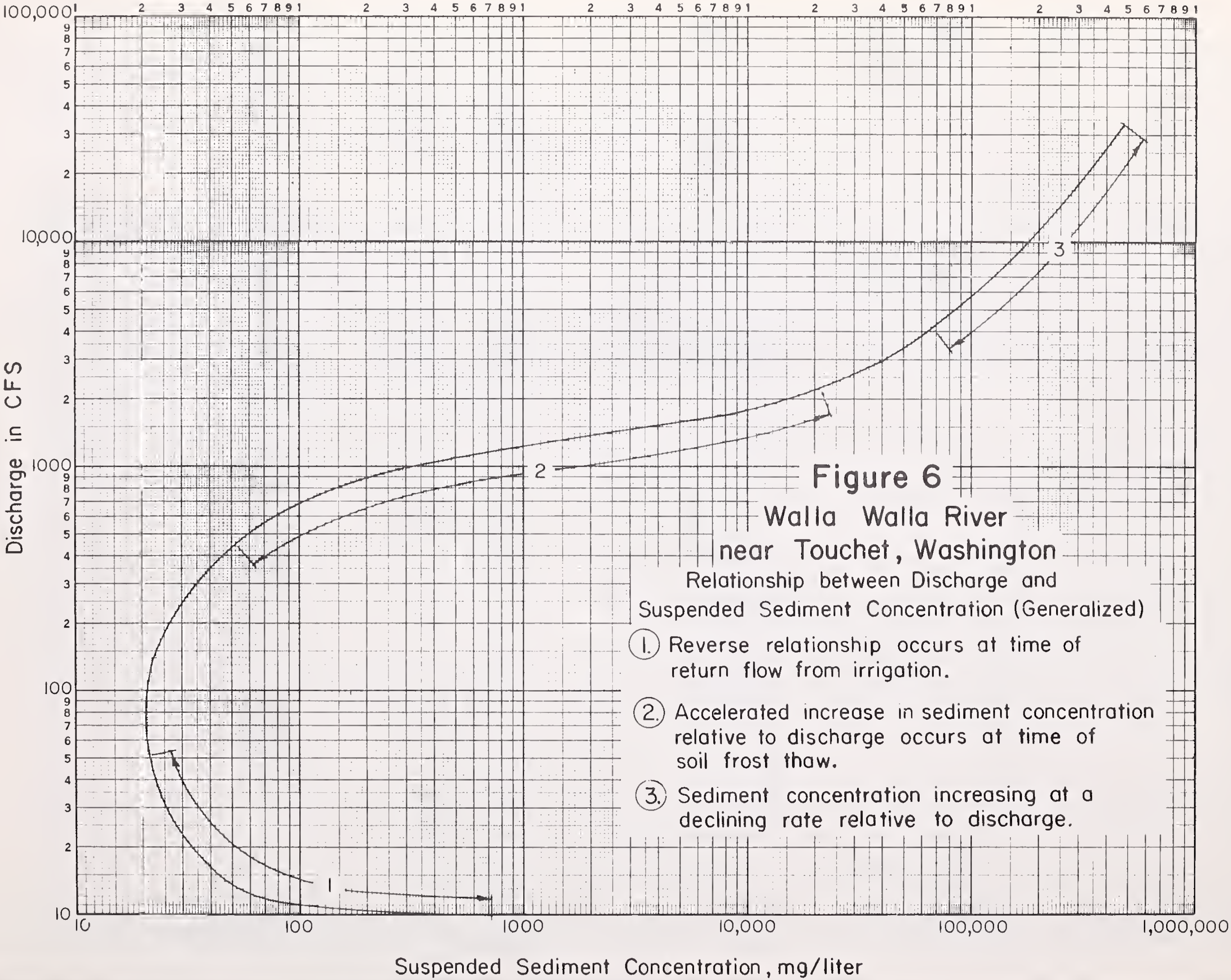
Figure 6
Walla Walla River
near Touchet, Washington
Relationship between Discharge and
Suspended Sediment Concentration (Generalized)
1. Reverse relationship occurs at time of return flow from irrigation.
2. Accelerated increase in sediment concentration relative to discharge occurs at time of soil frost thaw.
3. Sediment concentration increasing at a declining rate relative to discharge.
Discharge in CFS
Suspended Sediment Concentration, mg/liter
10
100
1000
10,000
100,000
1,000,000
1
2
3

and Oregon. Figure 6 is a plot of data from the Walla Walla River in southeastern Washington. The major condition bearing on sediment volume pertains to part 2 of the curve. This section reflects a rate of increase in sediment concentration many times that of discharge. This unusually large rate of increase is attributed to an acceleration of soil erosion with the thawing of several inches of surface soil frost. The frost layer remains below this depth, causing a relatively impermeable barrier to infiltration from the saturated layer that has thawed. Soil losses of as much as 300 tons/acre have been measured as runoff from rain or snowmelt rills the slopes that are bare or are in a poor cover of winter wheat. The combination soil frost followed by severe erosion does not occur every year, and therefore the relationships shown on figure 6 are not annual.

Part 1 of the curve in figure 6 is interpreted to be the result of return flow from irrigation. The relatively high concentration of sediment during the very low flows is diluted as discharge increases, hence the reverse nature of the relationship in this portion of the curve.

Part 3 of the curve reflects a discharge-sus-

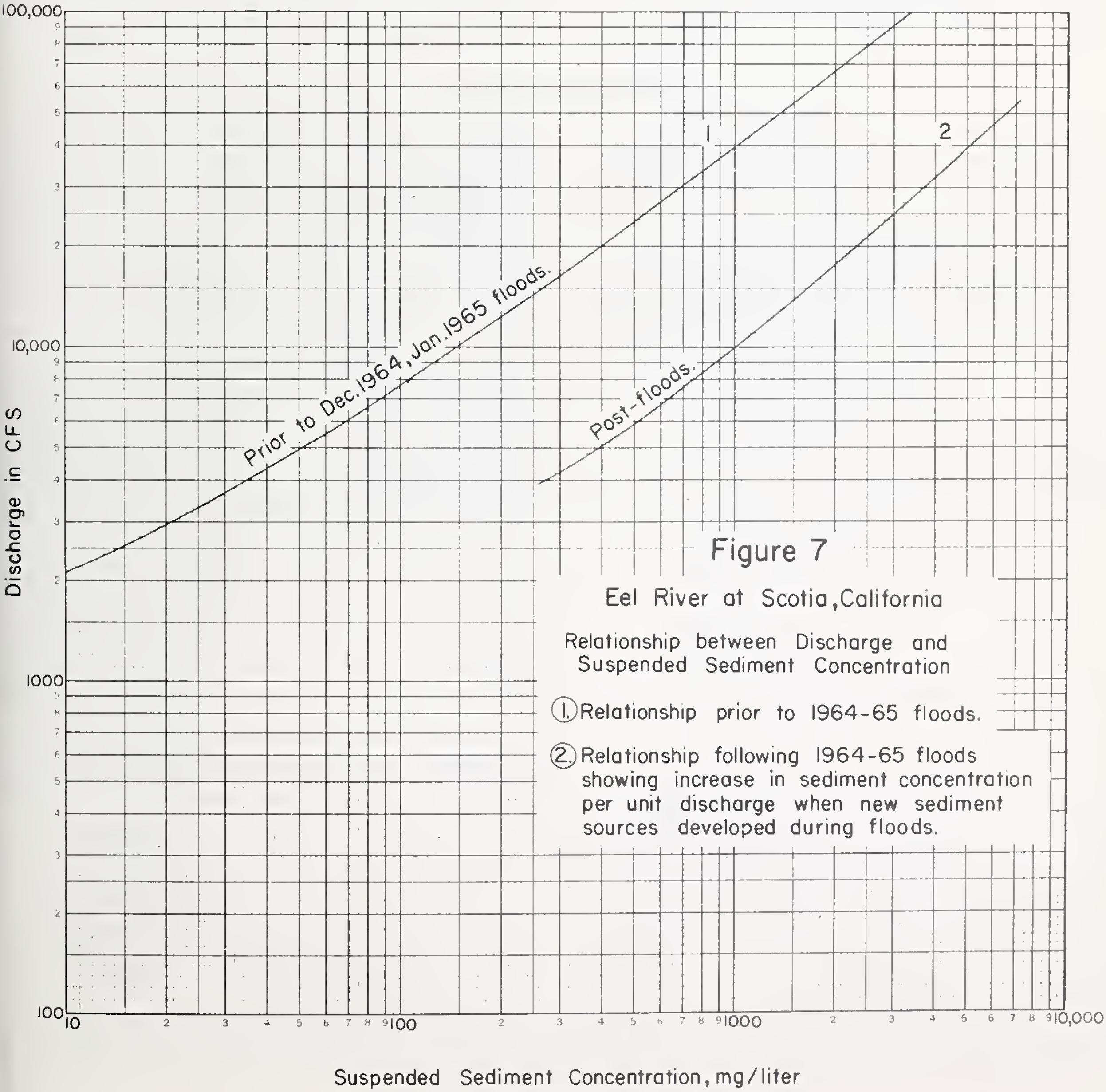

Figure 7

Eel River at Scotia, California

Relationship between Discharge and Suspended Sediment Concentration

1. Relationship prior to 1964-65 floods.

2. Relationship following 1964-65 floods showing increase in sediment concentration per unit discharge when new sediment sources developed during floods.

pended sediment concentration relationship as discharge extends to the level of rare occurrences; that is, sediment becomes available at a rate that is not in proportion to the rate of increase in discharge. This has been noticed in other records and indicates the error that may occur if a straight-line relationship is extended too far. On the other hand, the added stresses exerted on a watershed by a storm of rare occurrence may cause the development of new sources of sediment and rate of sediment availability greater than the rate of increase in discharge. This is illustrated in part 2 of the curve in figure 6. It is dramatically illustrated by the Eel River at Scotia in northeastern California. Curve 1 of figure 7 shows a portion of the discharge-suspended sediment concentration relationship prior to the exceptional floods of December 1964–January 1965. Curve 2 shows the shift in the relationship, indicating a manifold increase in sediment concentration with the same discharge. The Eel River Basin at the Scotia station is approximately 3,100 mi^2 in area. The average annual sediment yield per square mile is the highest recorded in the United States for this size of watershed. Major sources of sediment are landslides and bank erosion. The shift in the discharge-suspended sediment concentration curve is interpreted as a result of the enlargement of existing sources and the creation of new sources of sediment.

CONCLUSIONS

The procedures described for analyzing the relationship between discharge and suspended-sediment load data show that a variety of interpretive possibilities are available. The requirements for using these procedures are that an array of data on sediment concentrations be available to accompany discharge data, the latter preferably at a wide range of flows. Sufficient knowledge of the watershed should be available to relate sources of sediment to the characteristics of the plotted curves of data.

By employing this information on watershed characteristics as related to discharge-suspended sediment concentration relationships, knowledge can be built up to aid in determining (1) the dominant sources of sediment yield, (2) the approximate effect of these sources on sediment concentrations, (3) the approximate percentage of increase in sediment yield due to present watershed conditions as compared to what it would be under undisturbed watershed conditions, and (4) the effects of land treatment on the reduction of erosion and sediment yield.

Additional studies similar to those described should increase knowledge of the watershed conditions contributing to variations in sediment yield and in the improvement of the predictive tools that have been described.

VALLEY SEDIMENTATION AS A FACTOR IN SEDIMENT-YIELD DETERMINATIONS

By Stafford C. Happ[1]

SCS VALLEY SEDIMENT SURVEYS

Valley sedimentation between eroding areas and downstream points of sediment measurement or delivery is a common problem in efforts to evaluate sediment yields. Data on valley sedimentation are inadequate and cannot be improved without considerable effort.

Most of the pertinent information on valley sedimentation and related valley erosion is limited to results of investigations by the Soil Conservation Service during 1935–41. Those investigations began under the direction of Henry M. Eakin and expanded as part of the Agriculture Department watershed surveys, commonly called flood surveys, conducted jointly by the Soil Conservation Service, the Forest Service, and the Bureau of Agricultural Economics.

Valley flood-plain sediments were studied chiefly by auger borings, to measure and sample the "modern" deposits formed as a result of accelerated soil erosion following the clearing of forests and cultivation of sloping lands. The base of the modern sediment is generally marked by a dark soil horizon. Under natural conditions flood-plain sedimentation was too slow to prevent development of a dark surface zone throughout most of the United States east of the Rocky Mountains; farther west the conditions are little known and may have been more varied.

List of SCS Valley Sedimentation Surveys, 1935–41, in Which Ranges Were Profiled and Marked for Resurveys

1. Little Sioux River and 4 tributaries, below Cherokee, Iowa
2. Whitewater River and 6 tributaries, Minn.
3. Beaver Creek, Wis.
4. Coon Creek, Wis.
5. Kickapoo River and 2 tributaries, Wis.
6. Galena River and 4 tributaries, Wis.-Ill.
7. Upper Wabash River, Ind.
8. Muskingum River tributaries, Ohio
    - Killbuck Creek
    - Licking River and 6 tributaries
    - Piedmont Reservoir tributaries
    - Senecaville Reservoir tributaries
9. Ferguson Creek, S.C.
10. Coosa River tributaries, Ga.
    - Armuchee Creek
    - Noonday Creek
    - Pine Log Creek
    - Pumpkinvine Creek
    - Scarecorn Creek
11. Yazoo tributaries, Miss.
    - Coldwater River and 4 tributaries
    - Little Tallahatchie River and 12 tributaries
    - North Tillatoba Creek
    - Petacocowa Creek
    - Strayhorn Creek
    - Yocona River and 6 tributaries
    - Yalobusha River and 4 tributaries
12. Trinity River tributaries, Tex.
    - Battle Creek
    - Clear Creek
    - Muddy Cedar Creek
    - Salt Creek
    - White Rock Creek
13. Washita River tributaries, Okla.
    - Rush Creek
    - Sandstone Creek
    - Sugar Creek
    - Wildhorse Creek
14. Medicine Lodge River, Kans.
15. Arkansas River above John Martin Reservoir, Colo.
16. Middle Rio Grande, N. Mex.

The valley research was an extension of a reservoir survey program, with emphasis on sediment measurements to supplement reservoir data for evaluation of soil erosion rates and to determine sediment distribution relative to reservoir silting problems. Borings were made on ranges across valleys, surface profiles were surveyed along the ranges, and ends were marked with iron pipes. Related studies of sediment sources from stream channel and gully erosion were started, but the research program was curtailed before any surveys were completed as

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planned. The flood surveys were directed chiefly toward appraisal of sediment damage and prospective benefits from proposed remedial programs. For those purposes ranges were generally farther apart, as were borings on the ranges, and many ranges were not profiled or marked adequately for future recovery. Altogether, in both programs, sediment measurements were made in perhaps a hundred valleys of creeks and small and medium rivers, and ranges were profiled and marked, for future comparisons in at least 60 valleys, about half of them in northern Mississippi. The number depends on how confluent valleys are counted.

Figure 1 shows the location of valleys in which surveys included surface profiles and range markers for resurveys. The Arkansas, Middle Rio Grande, and Upper Wabash surveys covered only parts of those valleys, but others included tributaries; the entire watersheds are shown on the map. The Yazoo surveys were all on tributaries of that river, but cannot be separated on the scale of the map. The numbers on the map correspond to the accompanying "List of SCS Valley Sedimentation Surveys." The list is more complete, although perhaps there were a few more surveys that have not been verified. The list does not include all tributary names. Middle Rio Grande surveys involved only ground surveys without borings and were superseded by a much more elaborate program of the Bureau of Reclamation. About half of the Kickapoo borings were made on ranges previously established by the Corps of Engineers, which also has range surveys in the Little Sioux and Whitewater valleys and in valleys not covered by Agriculture Department surveys.

Scattered measurements of modern floodplain sediment, but without surface profiles or markers for future comparison, were made along tributaries of the Muskingum, Trinity, and Washita Rivers; along some tributaries of the

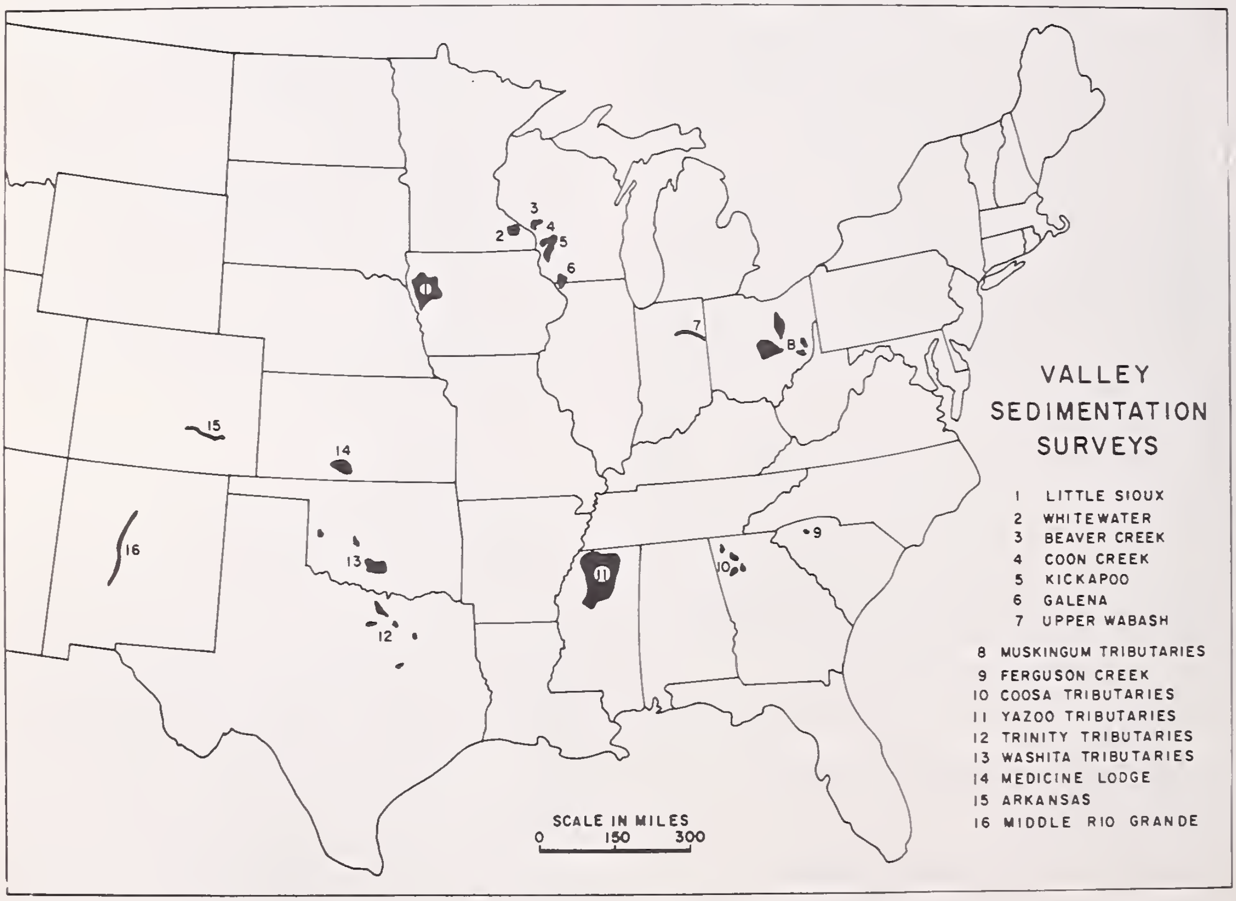


FIGURE 1.—Location of valley sedimentation surveys, 1935–41, for which ranges were profiled and marked for future recovery.

Potomac, Pee Dee, and Brazos Rivers; in valleys of the Boyer River (Iowa), Chariton River (Iowa and Missouri), Fabius and St. Francis Rivers (Missouri), Root and Zumbro Rivers (Minnesota), and Sny Creek (western Illinois); and in other locations for which information is not at hand.

The records of most of the sediment surveys are in the Cartographic Division of the National Archives or in Soil Conservation Service files, but efforts have failed to locate the Yazoo and Kickapoo data, which were left in Forest Service custody.

SEDIMENT DISTRIBUTION AND SEDIMENTATION RATES

The 1935–41 investigations indicated that flood plains had been aggraded by several feet (locally more than 20 ft) in small and medium valleys throughout much of the southeastern Piedmont; the loess belts east of the Mississippi River and bordering the Missouri River; the Driftless Area of southwestern Wisconsin and adjacent parts of Minnesota, Illinois, and Iowa; and sandy areas from southern Kansas to north-central Texas. Generally, the modern sediment was thinner and more difficult to distinguish farther downstream, and it was not determined whether such deposits are recognizable in lower valleys of major rivers. No definite area limits were established, and similar but lesser modern sediment was observed in many other areas east of the Rocky Mountains. Valleys farther west were not studied sufficiently to establish general conclusions. Scattered observations suggested relatively little valley sedimentation in glaciated areas of Northeastern States.

Particularly significant, relative to sediment-yield determinations, were concentrations of sediment relatively far upstream. Modern sediment was commonly recognizable up small headwater branches to within a few hundred feet of watershed divides, and in some valleys in Mississippi the thickest deposits were found near the head of permanent streamflow. Some 65 pct of the sediment was within the upper 6 mi of some Mississippi creek valleys. Thus a large proportion of the sediment was deposited upstream from most suspended-load measuring stations.

Very active soil erosion and sedimentation were apparent in all areas surveyed. Thus, it seemed reasonable to assume that the prevailing sedimentation rates were at least as high as the averages obtained from dividing total modern sediment by the number of years since the land had been settled (the period of accelerated soil erosion caused by agricultural practices). In the Whitewater Valley of southeastern Minnesota and the Kickapoo Valley of Wisconsin, buried fences and other datable objects indicated that prevailing sedimentation rates were about twice the average for the period of modern accumulation. Scattered evidence suggested similar increasing rates elsewhere, although the rates of increase may have been quite varied.

The estimated current sedimentation rate in the Kickapoo Valley, twice the average during the period of modern accumulation, was about 3 times the rate computed on the basis of sediment passing a gaging station near the mouth.[2] That would mean about 75 pct of the sediment yield had been deposited within a valley 60 mi long. Similar relationships were indicated by less complete data for the Whitewater Valley, and the Little Tallahatchie Valley in Mississippi. Similar but perhaps less extreme relations were suggested by volumes and distribution of sediment in some of the other valleys surveyed, although suspended-load records were not available for comparison.

Outside the known areas of general flood-plain aggradation, it seems probable that valley deposits may comprise a smaller proportion of the total sediment produced. That is not yet proven, however. Sediment loads in those streams are also probably lower, so that even smaller valley deposits may form a major proportion of the total sediment.

RESURVEYS

Resurveys have been made only in the Whitewater Valley and tributaries and in about half of the Yazoo River tributary valleys. The Whitewater sedimentation rate from 1939 to 1964 was about the same as the average for the previous 80 yr of accelerated erosion, but only about half of the current rate estimated in 1939. Figure 2

[2] Happ, S. C. 1944. Effect of sedimentation on floods in the Kickapoo Valley, Wisconsin. Journal of Geology 52: 53–68.

illustrates the changes on one Whitewater River range, where the flood plain is relatively narrow and the sediment is relatively thick. In some undredged valleys tributary to the Yazoo River the 1937–65 rate was about 30 pct below the average for the previous 100 yr. In both areas reductions are apparently due to conservation programs and changes in land use, and present rates are presumably even lower because of continuing reduction in sedimentation during the latter part of the period of record.

Most Yazoo River tributaries have been dredged, however, or trenched by erosion headward from dredged channels. In such valleys, channel and flood-plain erosion may now exceed the reduced overbank sedimentation, so that the valleys tend to become sources rather than repositories of sediment. Data are limited to widely spaced ranges and are inadequate for volumetric determinations.

In view of the apparent reductions in sedimentation rates, the old data cannot be applied directly to present conditions with any assurance. More resurveys are needed, and where there have been considerable changes, two successive resurveys may be necessary to establish current rates. More valley surveys in other areas will also be needed before valley sedimentation conditions will be adequately known.

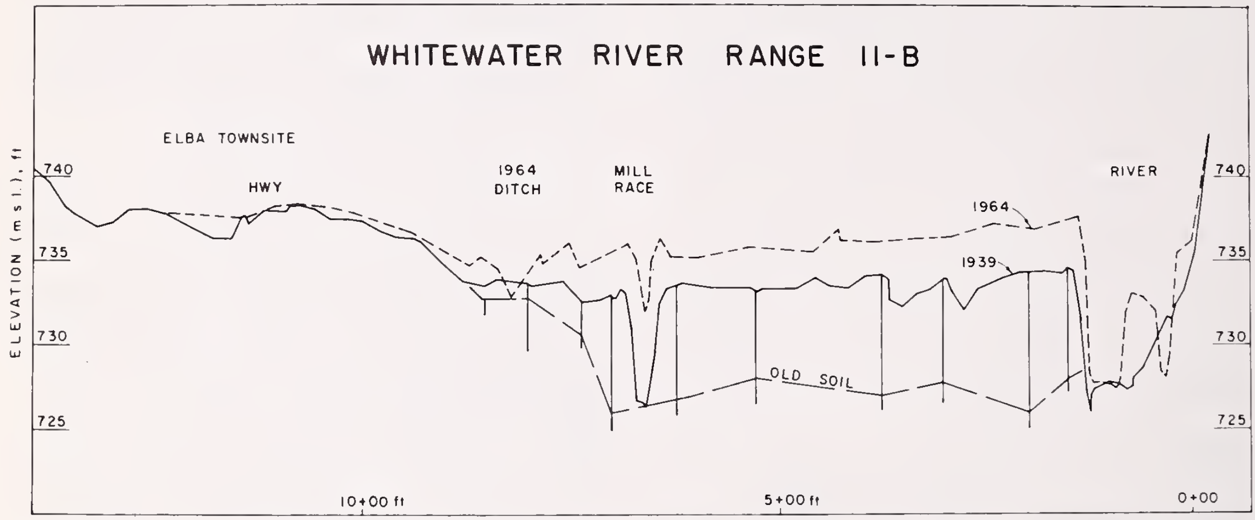


FIGURE 2.—Valley cross section showing modern sediment measured by 1939 borings and 1964 resurvey, Whitewater River, Minn.

CONCLUSIONS

Presently available data, although representative of only limited areas and largely out of date, indicate that valley sedimentation may account for as much as 75 pct of the sediment yield from agricultural watersheds. The relation may be reversed by ditching, and previously aggraded valleys may become additional sources of downstream sediment. Valley sedimentation and erosion are of such magnitude and are sufficiently widespread and diverse to require inclusion in calculations of sediment production based on suspended loads at downstream gaging stations and in calculations of downstream sediment yields based on erosion plots. More surveys of representative valleys will be required before reliable generalizations can be made concerning the relations of erosion to downstream sediment delivery.

SEDIMENT ROUTING WITH SEDIMENT-DELIVERY RATIOS

By Robert C. Boyce[1]

Soil Conservation Service watershed projects are commonly evaluated for a 100-yr life. For such evaluations, it is necessary to estimate sediment yields for 100 yr to establish sediment storage requirements for proposed dams or to compare with-project and without-project sediment yields in evaluating sediment damage. Sediment delivery ratios are defined and discussed by Renfro elsewhere in this publication. Determination of average annual sediment yield is shown in his example. After determining average annual sediment yields, project-life sediment yield is determined by multiplying the average annual yield by the appropriate number of years. If sediment yields were determined in this manner for each subarea in a watershed, it should be possible to route sediment through the watershed in much the same manner as hydrologists route storm runoff through watershed subareas.

Such a sediment-routing procedure requires that much of the sediment contributed to the stream system by subareas must somehow be removed from the routing as the drainage area increases. Otherwise, the sediment yield rate would not decrease with increasing area. For example, at the confluence of two subareas approximately equal in size, the total erosion times the sediment-delivery ratio for the total drainage area will be less than the sum of the erosion times the delivery ratio for each subarea. Because the relation of sediment-yield rate to drainage area usually differs from the relation of sediment-delivery ratio to drainage area only by a constant (see paper by Piest, Kramer, and Heinemann), the example may be restated as follows: The sediment yield for the total drainage area will be less than the sum of the sediment yields computed for individual subareas.

Sediment-yield rates are based on measurements of sediment in transport in the stream system (suspended load) or on measurements of deposited sediment. If we accept the premise that sediment-yield rates vary inversely with drainage area (fig. 1), then the decrease in sediment-yield rates with increase in drainage area cannot be explained as an upland phenomenon. This is because these rates are determined from sediment wholly within the stream conveyance system (stream channels, flood plains, and associated lakes, reservoirs, ponds, and swamps). Flood-plain deposition seems to offer a ready explanation. When a large watershed is considered as many small subareas, comparing sediment-yield rates of 65 pct of computed erosion (65-pct sediment-delivery ratio) for the small subareas at the left end of the sediment-delivery ratio curve (fig. 1)[2] with a sediment-yield rate of 5 pct of computed erosion (5 pct sediment-delivery ratio) for a large watershed at the right end of the curve indicates that 92 pct of the sediment yield from small subareas would not reach the mouth of a large watershed. If 92 pct of the cumulative sediment yield of small subareas does not reach the mouth of a large watershed, then massive and continual flood-plain deposition is indicated.

However, one of the basic premises of stream morphology (Playfair's law) requires that over a long time, a stream must transport essentially all sediment delivered to it. Lobeck[3] (p. 161) classifies streams according to their ability to transport sediment. His categories are based on transport power in excess of debris load (youth) and transport power in balance with debris load (maturity and old age). He does not have a category for debris load in excess of transport power

[1] Geologist, Central Technical Unit, Soil Conservation Service, U.S. Department of Agriculture, Hyattsville, Md. 20782.

[2] Roehl, J. W. 1962. Sediment source areas, delivery ratios, and influencing morphological factors. Extract of Publication No. 59 International Association of Scientific Hydrology Committee of Land Erosion, pp. 202–213.

[3] Lobeck, A. K. 1939. Geomorphology. 731 pp. McGraw-Hill, New York.

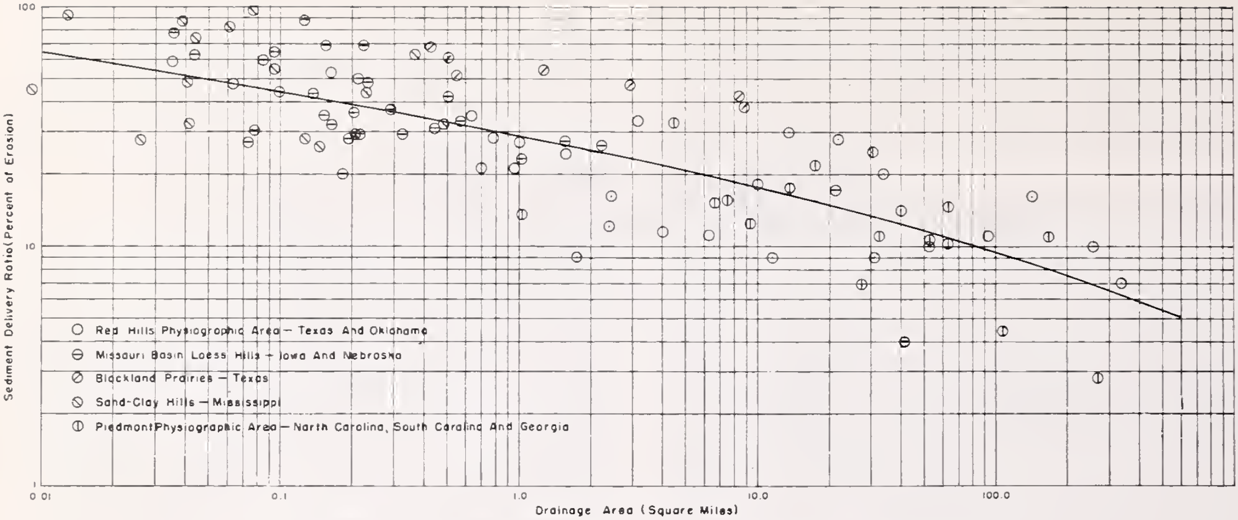


FIGURE 1.—Sediment-delivery ratio versus size of drainage area.

(continual flood-plain deposition). Leopold et al.[4] (p. 328) conclude that materials eroded from a drainage basin are only temporarily stored in the flood plain.

If it is assumed that a stream will, in 100 yr, discharge essentially all of the sediment it receives,[5] (p. 374) then the 100-yr sediment yields of subareas in a watershed may be accumulated sequentially in a downstream direction to arrive at the 100-yr sediment yield for any selected downstream point. Certainly, this assumption is questionable where long-term deposition or scour has occurred. In the absence of documented long-term deposition or scour, it seems reasonable that flood-plain aggradation is essentially balanced by flood-plain degradation over 100 yr. However, adding or accumulating subarea sediment yields derived from computed erosion times delivery ratio based on drainage area will give a watershed sediment yield reflecting the aggregate of subarea sediment-yield rates. This sediment yield will be higher than the watershed sediment yield computed by multiplying the computed erosion of the watershed by a delivery ratio appropriate for the watershed size.

Attempting to route or accumulate 100-yr sediment yields from subareas to arrive at a watershed sediment yield presents a problem: To conform to the sediment-delivery ratio curve, it is necessary to invoke continual flood-plain deposition and thereby violate Playfair's law. This dilemma might be resolved by examining the delivery-ratio concept to see if there might be inherent limitations, not apparent in current usage of the procedure, that would allow major departures from the curve for special conditions or situations.

If massive and continual flood-plain deposition does not satisfactorily explain the decrease in sediment-yield rates with increasing drainage area, then the sediment-delivery ratio must reflect not a stream process but an upland process. The sediment-delivery ratio then appears to be a measure of the efficiency with which computed erosion quantities are delivered to the stream system. The major components of the overland sheet erosion process are discussed by Meyer and Wischmeier.[6] During overland sheet flow, the movement of each entrained particle is essentially confined to a vertical plane perpendicular to the contour. The efficiency of this transport can be influenced only by variables that can operate in that vertical plane. Drainage area does not appear to be such a variable. Slope, however, is such a variable, and slope does vary with drainage area.

[4] Leopold, L. B., Wolman, M. G., and Miller, J. P. 1964. Fluvial processes in geomorphology. 522 pp. W. H. Freeman and Co., San Francisco.

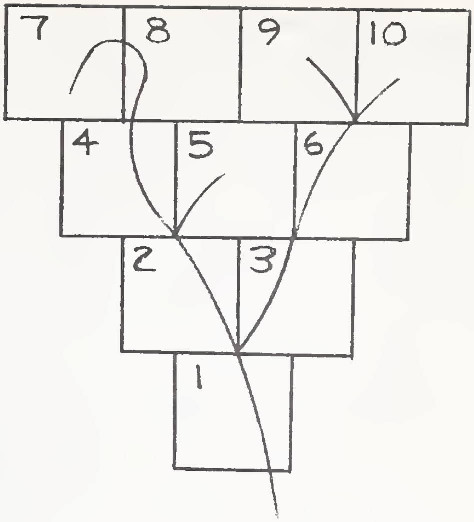
[5] Schumm, S. A. 1972. Fluvial geomorphology. *In* River Morphology, pp. 365–395. Dowden, Hutchinson, and Ross, Stroudsburg, Pa.

[6] Meyer, L. D., and Wischmeier, W. H. 1969. Mathematical simulation of the process of soil erosion by water. Transactions of the American Society of Agricultural Engineers 12: 754–758, 762.

According to Leopold and Maddock[7] (p. 22), average land slope decreases as drainage area increases. The relation between sediment-delivery ratio and drainage area is due to the fact that sediment-yield rates will decrease as the average slope decreases, reflecting a decrease in the efficiency of overland sediment transport. A decrease in average land slope as drainage area increases can occur only if assimilated downstream subareas, regardless of size, have low average land slopes. Only then can downstream subareas contribute to lowering the watershed average slope.

Having concluded that such low-slope downstream subareas must exist, one can see why they have remained unrecognized. They exist only as downstream subareas of a larger watershed and, as such, they are not separately represented on the sediment delivery ratio-drainage area curve. These low-slope, low-sediment-producing, downstream subareas affect the relation of sediment-delivery ratio and drainage area by decreasing the watershed-delivery ratio as they coalesce to increase watershed area and decrease watershed average slope. By isolating a class or category of subarea not represented by the sediment-delivery ratio curve, which has lower sediment-delivery ratios than those represented by the curve, an inherent limitation on the use of the sediment delivery ratio-drainage area relation has been delineated, and a solution has been found to the decreasing sediment-yield rate dilemma.

To see how the dilemma is resolved, consider a hypothetical watershed of 60 mi² composed of 10 equal subareas (fig. 2). Erosion is computed by the universal soil loss equation.[8] Only long-term average rates for sheet and rill erosion are being considered. Sediment-delivery ratios are from the sediment-delivery ratio curve (fig. 1). The reason for specifying 6-mi² subareas and a 60-mi² watershed is to allow the use of convenient delivery ratios (20 and 10 pct). The sediment yield of each subarea is 20 tons, and there are 10 subareas. The sum of the subarea yields is 200 tons, twice the watershed yield of 100 tons. Both



Watershed		*Subareas 1–10*	
Drainage area	= 60 mi²	Drainage area	= 6 mi²
Erosion	= 1,000 tons	Erosion	= 100 tons
Delivery ratio	= 10 pct	Delivery ratio	= 20 pct
Sediment yield	= 100 tons	Sediment yield	= 20 tons

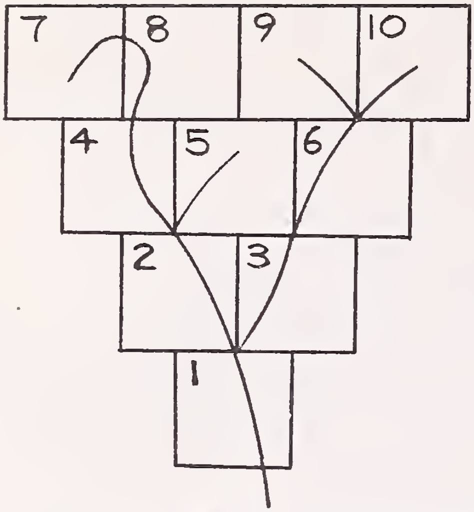
FIGURE 2.—A hypothetical watershed consisting of 10 subareas.

the watershed and the subarea computations appear to be valid applications of the sediment-delivery ratio. The dilemma is here: The difference of 100 tons (10 pct of the computed watershed soil loss) between the watershed yield and the sum of the subarea yields is too great an amount to be dismissed as flood-plain deposition.

In figure 3, note the two essentially different types of subareas: downstream areas with flow-through channels (subareas 1, 2, 3, 4, 6, and 8) and upstream areas without flow-through channels (subareas 5, 7, 9, and 10). Points on the sediment delivery ratio-drainage area plot represent the latter type. The sediment-delivery ratio curve does not represent the downstream, truncated subareas. Assuming that the sediment-delivery ratio curve is valid for the upstream subareas, delivery ratios of 20 pct are appropriate for subareas 5, 7, 9, and 10. The total erosion for these four subareas is 400 tons, and the sediment yield is 20 pct of 400, or 80 tons. The earlier estimate of 100 tons sediment yield for the entire watershed remains valid. By considering only 4 of the 10 subareas, 80 of the 100 tons of watershed yield are accounted for. Since the erosion on the remaining six subareas is 600 tons and since the sediment yield from these six areas must be 20 tons to give a watershed total of 100 tons, a sediment-delivery ratio of 3⅓ pct is indicated for

[7] Leopold, L. B., and Maddock, T. 1953. The hydraulic geometry of stream channels and some Physiographic implications. U.S. Geological Survey Professional Paper 252, 57 pp.

[8] Wischmeier, W. H., and Smith, D. D. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains. U.S. Department of Agriculture, Agriculture Handbook No. 282, 47 pp.



Subarea	Drainage area (mi²)	Erosion (tons)	Delivery ratio (pct)	Sediment yield (tons)
5,7,9,10	24	400	20	80
1,2,3,4,6,8	36	600	3⅓	20
1–10	60	1,000	10	100

FIGURE 3.—Sediment yields based on adjusted sediment-delivery ratios.

these six subareas. This does not appear unreasonable if it is assumed that sediment-delivery ratios and average land slope will vary in about the same manner. If the average land slope of the example watershed is 10 pct, and if 4 of the 10 subareas have average slopes of 20 pct, then the remaining watershed area must have an average slope of 3⅓ pct.

To complete the example, the sediment-delivery ratio for subarea 5 might be reduced to 10 pct because 5 is an interior subarea and could be expected to have lower average slopes than the peripheral subareas 7, 9, and 10. This change would reduce the total sediment yield of subareas 5, 7, 9, and 10 from 80 tons to 70 tons, and the average sediment-delivery ratio indicated for the remaining six subareas would increase to 5 pct. As shown in figure 4, subareas 1, 2, 3, 4, 6, and 8 are then assigned delivery ratios distributed around this average value of 5 pct, with the higher values going in the upper reaches and the lowest value going to the downstream subarea.

Table 1 and figure 5 show the complete sediment routing for this example. The valley sections represent cumulative values as distinct from individual subarea values. In a sediment-routing situation, the sediment-delivery ratio curve might be used as a guide in selecting delivery ratios for upstream subareas and a delivery ratio for the entire drainage area. Based on these upstream and downstream parameters, sediment-delivery ratios for intermediate subareas are selected so that, routing progressively downstream, the cumulative sediment yield of the sub-

TABLE 1.—*Sediment-yield routing*

Subarea	Valley section	Drainage area (mi²)	Erosion (tons)	Delivery ratios (pct)	Sediment yield (tons)
7	A	6	100	20	20
8		6	100	10	10
7+8	B	12	200		30
4		6	100	5	5
5		6	100	10	10
4+5+7+8	C	24	400		45
2		6	100	2	2
2+4+5+7+8		30	500		47
9		6	100	20	20
10		6	100	20	20
9+10	D	12	200		40
6		6	100	10	10
6+9+10	E	18	300		50
3		6	100	2	2
3+6+9+10		24	400		52
2–10	F	54	900		99
1		6	100	1	1
1–10	G	60	1,000	10	100

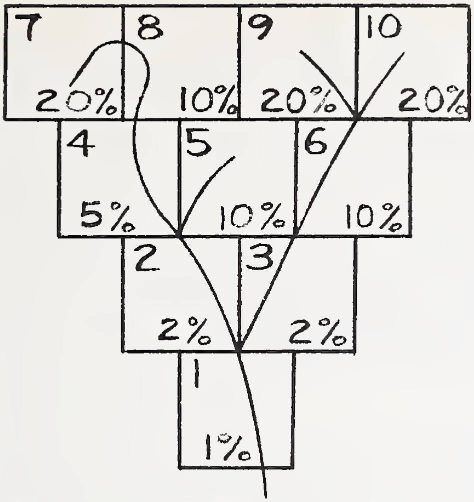


FIGURE 4.—Sediment-delivery ratio by subarea. Delivery ratios are shown as percentages.

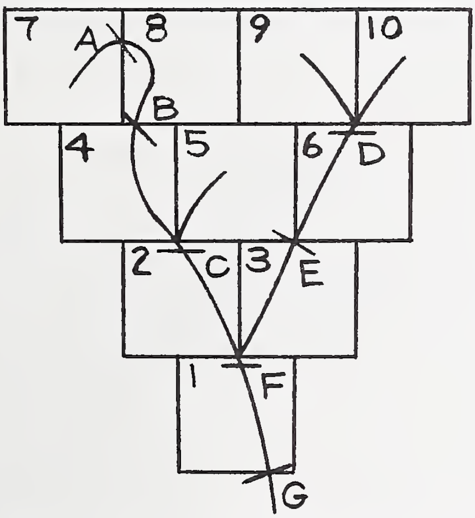


FIGURE 5.—Location of valley sections listed in table 1.

areas approximates the sediment yield from the entire watershed.

In a real watershed, as in this example, a constant assumed erosion rate may be used to derive subarea delivery ratios compatible with the watershed delivery ratio. These delivery ratios would then be applied to the actual computed erosion rates for each subarea. This method of deriving sediment-delivery ratios for downstream subareas would become tedious when applied to actual watersheds with many subareas of many different sizes. A computer program could, of course, be developed to do the job. Such computer-generated delivery ratios would be only a first approximation of a compatible subarea delivery ratio system. The system would require refinement and balancing based on judgment.

An alternative to this method of deriving sediment-delivery ratios would be to construct a delivery-ratio curve based on average land slope. Such a curve would be valid for both types of subareas discussed here. Because slope configuration, as well as steepness, influences the efficiency of overland sediment transport (Meyer and Wischmeier, cited in footnote 6), some kind of allowance for slope configuration would need to be built into the curve or applied in interpreting the curve.

If all independent variables in the universal soil loss equation except slope were random with respect to drainage area, then erosion rates might be expected to decrease as slope decreases with increasing drainage area. Erosion rates are generally independent of drainage area, and this expected slope effect fails to appear. Systematic decreases in the slope factor could not be offset by systematic changes in the slope length factor of the equation. Slope length has not been shown to vary consistently with slope or with drainage area and, in any case, is much less significant than the slope factor in the equation.

Because flatter land tends to have more intensive land use than steeper land, there would seem to be an indirect relationship between the unified soil loss equation cover factor and drainage area. In considering the relationship between the universal soil loss equation and drainage area, it is suggested that as drainage area increases and average slope decreases, the equation slope factor becomes less. At the same time, more intensive land use on flatter land causes an increase in the equation cover factor. This secondary and highly erratic cover factor increase overwhelms the slope factor decrease and insures a wide range of erosion rates. The net result is that erosion rates are generally independent of drainage area.

RELATIVE CONTRIBUTIONS OF SEDIMENT FROM SOURCE AREAS AND TRANSPORT PROCESSES[1]

By Henry W. Anderson[2]

INTRODUCTION

In evaluating the relative contribution of sediment sources and transport processes that affect streams in forests, we face problems of what sedimentation characteristics should be considered, where in the watershed the characteristics were measured or determined, and how well we sampled their time and spatial variations. In evaluating the contribution of the sediment sources, we must also consider the unique characteristics of the environment; that is, the hydrologic characteristics of the soil mass, the terrain situation which the soil mass often occupies, the erosional processes, and the high sensitivity of each process to change.

Typically, forest soils show wide variation in physical characteristics associated with the geologic origin of the parent material and variation in weathering processes. Soils anchored by tree roots often occupy slopes which would be beyond the natural angle of repose for the geologic material. The steep slopes are subject to an erosional process that consists of channel cutting over long periods, mass soil creep, and soil occasionally sliding from lower slopes into the channel. Erosion is but one of the three basic processes of sedimentation; the other two are sediment transport and deposition. Each of the three processes may in turn serve as a source of sediment, or be involved in the transport process—depending on the particular measurement of sediment delivery being considered.

Let me define what I mean by each of the three basic processes. Erosion is the detachment or initial spatial displacement of soil, rock, or organic matter by whatever agent in whatever state. Sediment transport is the movement of erosion end products after initial displacement, including illuviation of particles downward into the soil or rock. Deposition is temporary or permanent halting of a portion of transported erosion products.

In this symposium we are emphasizing forest land use and stream environment. I will concentrate on sediment sources and transport processes that affect the stream environment in terms of contributing to streamflow quality or to stream channel characteristics. Let me work backward from various measurements of delivery of stream sediments to the transport processes and finally to the sediment sources.

MEASURES OF SEDIMENTATION

Measures of sedimentation depend on the measuring device, where sediment is measured, and the representativeness of our sample of time variation of sediment-producing events. The usual measures of sediment include sediment deposition as in reservoirs or channels, suspended-sediment concentration in streamflow, and bedload movement. Each of these measures may be expressed in a variety of ways that are most meaningful to particular kinds of damage (or sometimes benefits) associated with the sedimentation.

[1] Paper originally presented at the Symposium on Forest Land Uses and Stream Environment, Oregon State University, October 19–21, 1970.

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DEPOSITION MEASUREMENTS

Deposition of sediments may be measured in reservoirs, in channels, or sometimes in natural lakes or lagoons. Deposition in reservoirs probably comes closest to being measures of the total sediment delivery from watersheds. However, this measure is true only if the reservoir is large enough to insure nearly 100 pct efficiency in trapping all the incoming sediment; otherwise, corrections for trap efficiency must be made, often by measuring the reservoir capacity per unit of water inflow.

Measurement of deposition is performed in several ways: by a series of ranges or points that determines the height of the sediment in a reservoir at two or more separate times; by probing sediment to determine its depth; or by seismic determination of sediment depth. Loss of reservoir capacity in relation to the frequency at which that capacity would be utilized is a common measure of the damage associated with the sediment. Other measures consider the effects of sediment on water quality and shore and bottom environments.

Sediment deposition in the channels, lakes, or lagoons may be determined by the same methods used in reservoirs; however, the damage associated with these depositions varies. Damage from channel depositions may result if the channel's capacity to carry flood flows is limited; hence, an area may be flooded unless a channel has full capacity. The effects of different materials deposited in channels and even the time or sequence of depositions of different sizes of materials will be discussed in several papers at this symposium. Deposition in lakes and lagoons may necessitate removal by excavation or may result in esthetic damage or damage to natural habitats. Thus, deposition of sediment is one of the important measures of sedimentation because it is responsible for a variety of damage.

CHANNEL-TRANSPORTED SEDIMENTS

Sediments transported in channels are usually considered in two categories, suspended sediment and bedload sediment discharge, although in many circumstances no clear distinction can be made. Suspended sediment in streamflow is commonly measured, both because of its importance in water quality and because it is considered to be a useful index of total sediment discharge and future expected sediment deposition. In a recent appraisal of water quality in the United States, suspended sediment was said to be 80 pct of the problem. Although suspended sediment is often used as an index to total sediment discharge, it may vary widely as a proportion of the total land load. Suspended sediment in the Rhine River, for instance, is said to be only 10 pct of the total load; in contrast, it is said to be 96 pct of the total load in the Eel River at Scotia. The proportion of bedload can also vary rather widely within parts of single watersheds.

Meaningful measurements of suspended sediment may involve determination of the total suspended load; the distribution of sediment concentrations, either expressed as a percentage of the days of the year or of the total volume of water with various sediment concentrations; or the sediment concentrations at various times of the year.

Total suspended-sediment discharge from watersheds has been determined in two principal ways. In the first way, sediment is measured often enough in a year so the sediment concentration curve may be shown in relation to the streamflow discharge curve. Then, a simple product of sediment concentration times day-by-day waterflow is considered total sediment discharge. The second way (the so-called flow-duration method) associates sediment concentration with discharge (fig. 1). Discharge times the

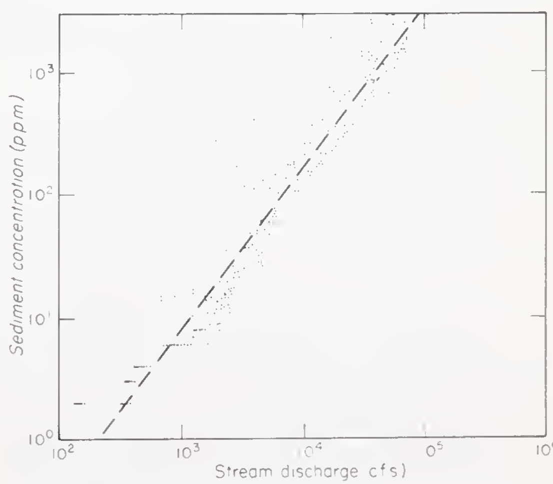

FIGURE 1.—Increase in sediment concentration with increase in stream discharge, Eel River at Scotia, 1958.

probability of that discharge times sediment concentration yields expected sediment discharge for expected streamflow. The first method gives a sediment estimate for a particular year; the second method gives an estimate of average expectancy under the conditions of streamflow and watershed conditions. For years with average streamflow distribution, the two methods give essentially the same results (*15*).[3] Anderson (*1, 2*) and Wallis and Anderson (*15*) used the flow-duration method to determine average expected total sediment discharge for 29 streams in western Oregon and for 23 to 31 streams in northern California.

[3] Italic numbers in parentheses refer to items in "Literated Cited" at the end of this paper.

SUSPENDED-SEDIMENT SOURCES AND CAUSES

Two of these studies related suspended-sediment production from watersheds to basic causes and sources on the watersheds. The general model was as follows: Suspended sediment produced by a watershed=*f* (meteorological, terrain, land use and condition, soil characteristics). Both the study of 29 watersheds in Oregon (*1*) and the study of 23 watersheds in California (*15*) used multivariate analysis of the relation of suspended sediment to the cause-variables in the watersheds.

One result of the Oregon study was the proportioning of sediment contributed by forest, agricultural land, and main channels. Another result was a prediction of expected future increases in sediment production from forests of western Oregon because of future road development and logging. If we assume that future logging will be as effective as past logging and that projected road development will follow past patterns and eventually occupy 6 pct of each watershed, we may expect sediment to increase by a factor of four. Eighty pct of the increase would be associated with road development, and 20 pct with logging independent of roads. Such increases would inevitably change the relative contribution of source areas versus channel erosion.

The study of California watersheds estimated the following increases in sediment production associated with present average land uses as contrasted with absences of such land use in the watersheds:

1. Conversion of 14.8 pct of steep watershed lands from brush or tree forest to grassland multiplied sediment by 4.7.

2. Fires in the last 10 years on 5.3 pct of the watershed areas multiplied sediment by 2.3.

3. "Poor logging" of 1.4 pct of the area increased by 26 pct.

4. Conversion of 0.6 pct of a watershed into low-standard roads increased sediment by 24 pct.

Thus, associated with these four factors of man's use was a 17-fold maximum increase in sediment. One of the largest future potentials is indicated for roads, if projected roads eventually occupy 6 pct of the area rather than 0.6 pct as has been the case in the past.

Geologic type	Surface/aggregation ratio (cm ^{2}/pct)	Silt + clay (pct)	Gravel (pct)
Recent volcanic (QV)	275	17	10
Young volcanic (QPV)	204	20	26
Columbia basalt (PMv)	59	20	60
Marine sedimentary (M-K)	46	28	54
Jurassic-Triassic (JTR)	53	19	66
Devonian (D)	23	20	77
Eocene volcanic (Ev)	17	40	47

An earlier study of suspended-sediment discharge in western Oregon (*1*) included an analysis of the effect of watershed variables on suspended sediment expressed as average number of turbid days per year. The relations obtained between turbid days and soil and geology of watersheds are pertinent to the objective of this symposium. The analysis showed that the number of turbid days (days on which suspended sediment in the streamflow was more than 27.5 p/m) was related to the amount of silt plus clay in the watershed soils, the surface/aggregation ratio of the soils (*1*), and the percentage of gravel in the soils. The range in number of turbid days between watersheds was from 5 to 204 d/yr. The range between watersheds of each soil variable and the independent effect of that range on the number of turbid days was as follows: silt plus clay (range 19.1–29.2 pct)—2.34; surface erodibility index (range 26–178)—8.55; and gravel in soils, >2 mm (range 17–67 pct)—0.23.

To illustrate, the results showed that a watershed soil with 29.2 pct silt plus clay had 2.34 times as many turbid days as one with 19.1 pct silt plus clay. Soil erodibility was also important, and gravel content of soils of 67 versus 17 pct decreased turbid days to less than one-quarter. The study showed that turbidity of the streams was highly related to the soil characteristics, and these were predictable from the geology in the watershed. (See table on page 68.)

CHANNEL PROCESSES

Transport physics and channel stability and permeability may influence the relative contribution of sediment sources and channel processes to sediment discharge from watersheds. The basic properties that control the transport of sediment in channels include the volume of water, the excess weight of the solids over that of a like volume of the water, the mean rate of potential-energy loss as the flow descends the gravity slope of the stream, and the efficiency rate of the transport work done. The efficiency rate involves the relative velocity or slip velocity between the water and the sediment particles (*3*). The excess weight of particles fine enough to be carried in suspension is supported by the upward forces exerted on the grains by the eddies of internal turbulence. The potential-energy loss in the falling particles as sediment moves down a normal stream is 130 times as great as the energy required to maintain the particles in suspension (*9*). In the transport of bedload, the excess weight is supported by periodic contact with the bed, the bedload moving by jumps (*3*).

The volume of water in a stream may not be constant. Loss of volume by percolation into stream channels or into bank storage or even by overflow of channel banks at some places may cause deposition because of loss of velocity. On the other hand, rising ground water within the channel may initiate motion in particles which would not be moved under ordinary stream velocities. Clayton et al. (*5*) reported for a stream in Alaska that rising ground water increased the competence of the flow to move bedload by a factor of 1,000. Ground-water inflow in effect lifted the whole streambed into movement, starting rapid sediment transport. The opposite effect of water percolation into channel bottoms and into bank storage is a familiar phenomenon in initiating sediment deposition in arid land channels; both percolation and rising ground water may sometimes be important phenomena in humid forest environments.

That channel processes and the energy involved may create sediment is indicated by the intuitive idea of internal grinding of material during transport of sediment. We may express quantitatively conversion of bedload to suspended load by examining some estimates of bedload for two reaches of the Eel River in California (*4*), and some data on the total suspended-load discharge published by the U.S. Geological Survey (*14*). Brown and Ritter (*4*) estimated the bedload to be 30 pct of the total load in the upper reaches of the Eel River and only 4 pct of the total load at the downstream discharge point at Scotia. There is no evidence that bedload is being lost by deposition in downstream channel reaches, so we may hypothesize that bedload is partly converted to suspended load between the upper and lower channel reaches. With some minor assumption, such as the breakdown of sediments being proportional to the river-miles traveled, we may make the following estimates of the conversion of bedload to suspended load and estimates of the converted suspended load in the upper, middle, and total watershed:

Area	Drainage (mi^2)	Sediment (million tons/yr) Suspended	Bedload	Total	Bedload contribution to suspended sediment
Upper Eel	1,132	6.3	2.7	9.0	3.3
Middle Eel	1,632	15.5	−1.7	15.5	4.9
Total	2,764	23.5	1.0	24.5	8.5

We see that 89 pct or 8.3 million tons, of the total of 9.3 million tons of bedload generated in the whole basin become suspended load in traveling through the channels to the watershed discharge point at Scotia. These figures help explain the higher suspended-sediment concentrations in the lower Eel than in the upper tributaries, and might have important implications in sediment control.

SURFACE EROSION

Surface soil erosion—another basic division of sedimentation—consists of two processes, mass movement and surface erosion. Mass movement has usually been divided into two parts: soil creep; and a variety of soil, debris, and rock slides. In surface soil wash erosion, the usual sheet erosion, rill erosion, and gully erosion are frequently studied.

Surface erosion is usually measured by means that do not permit direct accounting for its contribution to sediment transported or to sediment discharged from watersheds. In the usual methods, eroded material is caught in troughs, or change of soil depth is measured by pins or transects. Because trough catches are usually from plots that are less than full-slope length, the slope erosion process is restricted by the plot, and erosion measurements are low. Measurements by pins are frequently faulty; they confound loss of soil with compaction and illuviation of particles. The use of transects has the same limitation except where erosion is gross, such as by gullying. Limitations in the techniques for direct measurement of surface erosion make it difficult to determine the effects of differences in forest land use and management on erosion-induced damage.

Surface erosion by overland flow at forest sites is usually associated with intense rainstorms that follow baring of the soil by roads, fire, overgrazing, mass soil movement, or other causes. Some appraisal of the contribution of these sources to sediment discharge from watersheds has been made.

MASS SOIL MOVEMENT

The general role of landslides versus other processes in contributing to sediment discharge from watersheds was determined for the Pacific Southwest Interagency Basin Survey (*12*). The contributions of landslides, streambank erosion, and land surface erosion to sediment discharge from the north coast watersheds of California were estimated as follows:

	Pct
Landslides	25
Streambank erosion	55
Land surface erosion	20

For the same general area, Kojan (*8*) evaluated the role of soil creep erosion in contributing to total sediment discharge. He related measurements of soil creep on slopes to the total channel slopes involved and estimates of soil depth. His evaluation indicated that soil creep was contributing about 750 tons/mi^2/yr to sediment encroachment on channel banks; this encroachment would then contribute to sediment discharge. Thus, of the average total sediment discharge of 4,880 tons/mi^2/yr (*15*), soil creep contributed about 15 pct.

STREAMBANK EROSION

I determined the contribution of streambank erosion to sediment discharge in the Willamette Basin of western Oregon, after evaluation of sediment contributed from forest lands and erosion of agricultural lands (*1*). The U.S. Army Corps of Engineers determined the length of eroding channel banks (*11*). The total sediment discharge annually from the basin above Salem was 1,995,000 tons. Of this tonnage, the proportion attributed to three factors was as follows: from the 5,460 mi^2 of forest land—24 pct; from the 1,820 mi^2 of agricultural land—22 pct; and from the 205,000 ft of eroding main channel—54 pct.

These data are for the condition of channels and forests and agricultural lands in 1950; with the channel rectification, construction of major reservoirs, and perhaps other changes in the watershed, other breakdowns of sediment discharge from the Willamette Basin might now be occurring.

Other studies have indicated the importance of channel-bank erosion in stream sediment discharge. Striffler (*10*), in a study of the trout habitat of streams in Michigan and the relation of sediment to that habitat, concluded that 28 pct of the sediment production was associated with streambank erosion. The literature seems particularly barren of quantitative relationships of the role of land surface erosion in causing streambank erosion.

EFFECTS OF MAJOR FLOODS

We might think that large watersheds were relatively stable and that variation in the sediment discharge from watersheds from year to year are related closely to the rain and snowmelt events that produce streamflow, at least under constant land use and development. As far as we could detect from recent records, this had apparently been true for some time before the appearance of the major floods of December 1964. Now we have evidence that the watersheds were changed for some period after the flood, and the magnitude of change depended in part on the land use and condition of watersheds that the flood found.

Four recent studies give some quantitative expression to changes in sedimentation after these major floods. One study reports increases in suspended-sediment discharge from 16 watersheds associated with the floods and land use conditions before the flood in northern California (*2*). Other data, simply comparing sediment concentrations before and after the flood, will be given here. Two studies report on surveys of landslides after floods in Oregon.

Dyrness (*6*) found that, on the H. J. Andrews Experimental Forest, the number of landslides per 1,000 acres produced by the 1964–65 floods, for three types of land use, was as follows:

Land use	*Landslides/ 1,000 acres*
Undisturbed forest	0.4
Logging	3.9
Road construction	125.9

Similar results were found in a general survey in western Oregon forests of 725 soil and debris slides found after the 1964–65 floods (*13*):

Land use	*Slides (pct)*
In undisturbed areas	22
Associated with logged areas	24
Associated with roads	54

SUSPENDED SEDIMENT

Changes in the average sediment concentration in streamflow is another measure of the effects of major floods on sedimentation. Sediment concentration for like flows (long-term flow probabilities) during 1963 before the 1964 flood and during 1967 after the flood for two streams in northern California and for the south Umpqua in Oregon showed the following differences:

Watershed	Suspended sediment (p/m)		Ratio *A/B*
	Before	After	
Van Duzen	2,050	4,040	2.0
Trinity	117	430	3.7
South Umpqua	100	205	2.0

Of course, the increases in the sediment concentration times the volume of streamflow gives the increase in suspended sediment discharge. Such increases were determined for 16 northern California watersheds and the relation of magnitude of the increases to watershed characteristics and land use was determined by principal components analysis.

In a study reported in 1970 (*2*), I found that high-elevation watersheds suffered greater increases in sediment discharge from the major floods than low-elevation watersheds. Sediment increases in high-elevation watersheds averaged three times those in low-elevation watersheds. The average area of "poor logging" in the watersheds—logged areas where the roads were adjacent to streams and landings were in draws—was 19.2 acres/mi^2 of the watershed. Compared with watersheds having no such poorly logged areas, sediment rates in the first year after the flood increased by 30 pct for 18-yr-old logging and by 200 pct for 4-yr-old logging. For the second year after the flood, the average sediment discharge increase was 94 pct of the first-year increases; for the third year, it was 66 pct.

The effect of this major flood on channels is illustrated by a U.S. Geological Survey study of the Eel River (*7*). The streambed of the upper Eel River, after the flood, rose some 6.7 ft over that of the preflood bed height (fig. 2). If we convert this rise to total deposition in the three upper Eel River tributaries, we get an estimate of about 23,000,000 tons deposited in the channels. This would amount to an 8-yr equivalent in bedload. Since we have previously calculated that 89 pct of the bedload from these upper reaches eventually becomes suspended load, we can ex-

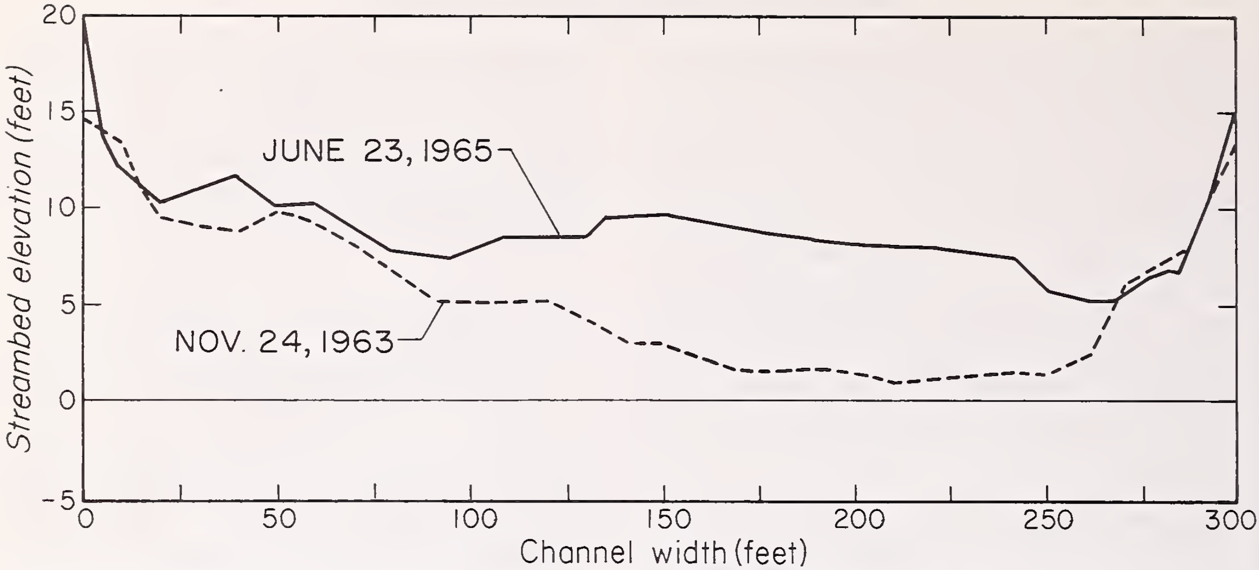

FIGURE 2.—Sediment deposition in channel cross section following December 1965 flood, Middle Fork Eel River below Black Butte River. (From reference 7.)

pect increased sedimentation from the Eel River associated with the major flood and the associated land conditions in that basin to persist for many years. The Eel at Scotia actually showed such a persistence of high sediment discharge—24 million tons in 1966 and 23 million tons in 1967, compared with preflood sediment discharge of 13 million tons/yr.

CONCLUSIONS

Quantitative measurements of soil characteristics, topography, and land-use conditions and the meteorological impacts of these lands have provided the basis for predicting differences in expected sediment production from these sources. Several studies have reported evidence of contributions of sediment from channel banks, from mass movement into channels, and from channel bed materials. We have first approximations of expected effects of land-use developments on future sediment discharge from watersheds. And we have some evidence that combinations of major flood-producing storms and conditions of watersheds have produced higher sediment discharge than experienced in the recent past. The wealth of quantitative information now accumulating promises to provide us in the future with more exact determinations of the relative contribution of sediment sources and transport processes.

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SEDIMENTATION IN RELATION TO LOGGING ACTIVITIES IN THE MOUNTAINS OF CENTRAL IDAHO

By Walter F. Megahan[1]

INTRODUCTION

I was asked to report on the topic "Sediment Yields Related to Logging Activities." However, this general topic has been considered in detail by a number of researchers in recent years (*5, 9, 10, 13, 15*).[2] I think it would be of more interest to review the past and current research of the USDA Forest Service, Intermountain Forest and Range Experiment Station, dealing with the effects of logging on sedimentation in the high-erosion-hazard areas found in the Idaho Batholith.

The Idaho Batholith is a 16,000-mi² expanse of intrusive, acid, igneous rock in central Idaho (fig. 1). Various granitic rocks are found in the batholith, but quartz monzonite predominates. Soils developed from these granitic rocks generally have coarse loamy sand to sandy loam textures; they have little cohesion because of their low silt and clay contents (typically 10 and 5 pct, respectively). Similar soils developed from granitic parent materials were the most erodible to be found in Oregon and northern California (*1, 2*). Large-volume rainstorms or large quantities of snowmelt or both are common.

Most of the topography in the batholith is mature, having steep slopes separated by narrow ridges and valleys. The combination of steep topography, extreme soil erodibility, and high climatic stresses creates extreme erosion hazards even on land in the undisturbed state. Soil disturbances in areas of this type can increase erosion and subsequent sedimentation tremendously. Fortunately, such high-erosion-hazard lands are not found uniformly throughout the entire batholith. There are limited areas where erosion hazards may be moderate or even low because of moderated relief (caused by glaciation or diastrophism) or soils with reduced erodibility (predominantly caused by loess deposits on top of residual soils). The early logging in the batholith was concentrated on the more accessible of the low-erosion-hazard lands because the gentle relief facilitated operations. However, by about the mid-1950's, most of these lands had been logged, so operations were extended to the higher-erosion-hazard areas.

The Forest Service has been studying the effects of logging on erosion and sedimentation on such high-erosion-hazard areas since 1960. The sedimentation studies concentrate on three primary problem areas, which are to characterize sedimentation on undisturbed watersheds, to quantify the effects of logging and the attendant road construction on such watersheds, and to evaluate the downstream impacts of accelerated sedimentation and the duration of effects. I will outline the kinds and amounts of data that are available as well as some of the results of our studies to date.

SEDIMENTATION ON UNDISTURBED WATERSHEDS

We define undisturbed watersheds as being free from extensive activities of man, e.g., logging, grazing, etc., except as noted in table 1. To date, we have collected 82 station-years of data on 14 perennial watersheds ranging in size from 0.10 to 2.54 mi². The dominant timber species on all 14 watersheds are ponderosa pine, *Pinus ponderosa* Laws, and Douglas-fir, *Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco. These watersheds are representative of the range of conditions found on the high-erosion-

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[2] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this paper.

FIGURE 1.—Location map of the Idaho Batholith.

hazard lands in the Idaho Batholith. Elevations on the 14 watersheds range from 3,000 to 7,000 ft; side slope gradients average about 60 pct, and channel gradients range from 14.9 to 31.8 pct (table 1).

Data Collection

The soils in the batholith are coarse textured; size fractions for a typical soil are shown in table 2. Note that there is considerable coarse sand and fine gravel in these soils; however, little of the gravel is larger than 7.9 mm. This particle-size distribution results from the nature of the granitic bedrock.

The settling velocities are high for most of the soil particles (table 2). Thus, most sediment in this area is carried in the form of bedload; in fact, the streams are generally crystal clear, becoming slightly turbid only during peak-flow periods.

Under such conditions we have been able to use small detention reservoirs to measure sediment yields. By this means, water levels are not altered except by natural changes in streamflow. Storage capacities of these reservoirs range from about 15 to 180 yd^3/mi^2 of drainage area, and sediment accumulates to approximate maximum depths from 4.0 to 7.0 ft. To maintain adequate storage capacity, we flush each reservoir periodically to remove all accumulated sediment, which otherwise would remain submerged at all times. Every spring and fall (on or about June 1 and October 1), we use a network of closely spaced cross sections to measure the amount of sediment deposited in each reservoir.

During high-water periods in 1963, we collected a series of suspended-sediment samples of the overflow at the spillway of one of the dams and compared these samples with the total sediment stored in the reservoir. The results showed that the trap efficiency of this reservoir exceeded 80 pct. Similar high-trap efficiencies were reported by Leaf (*8*), who determined that debris basins trapped virtually all the sediment produced from high-elevation watersheds in Colorado, where soil textural properties are quite similar to those in the batholith.

Sediment Yields

The sediment-yield data shown in table 1 have not been corrected for trap efficiency because this information has not been determined for all dams. However, our preliminary data suggest that the tabulated values are at least 80 pct of the actual sediment yields. Note that average annual sediment yields for these undisturbed watersheds are rather low, ranging from 4.5 to 26.9 $yd^3/mi^2/yr$. Leaf (*8*) reported average sediment yields of 9.1 and 6.2 $yd^3/mi^2/yr$ for two undisturbed forested watersheds in the Rocky Mountains in Colorado.

As might be expected, the data for the individ-

TABLE 1.—*Available annual sediment production data on undisturbed*[1] *study watersheds in the Idaho Batholith*

Drainage	Area (mi^2)	Mid-elevation[2] (ft)	Dominant aspect	Mean channel gradient[3] (pct)	Period of record: Water years	Period of record: Total years	Sediment yield ($yd^3/mi^2/yr$): Mean	Sediment yield ($yd^3/mi^2/yr$): Standard deviation
Cabin	0.40	5,030	SE	14.9	1966–72	7	22.6	24.2
Control	.78	5,240	SE	15.2	1966–72	7	4.5	3.8
Eggers	.50	5,685	SE	22.0	1966–72	7	16.0	13.0
Ditch	.41	5,350	SE	20.8	1966–72	7	33.8	30.4
C	.75	5,835	SE	21.5	1966–72	7	23.3	16.6
D	.47	5,789	SE	24.2	1965–72	8	22.8	15.5
K-1	.10	5,325	NW	31.5	1966–72	7	26.9	31.7
Tailholt Main	2.54	5,665	SE	25.9	1961–67	7	5.8	6.8
Tailholt A	.84	5,945	SSE	31.1	1968–71	4	21.8	16.9
Tailholt B	.61	5,610	SE	30.9	1968–71	4	26.8	20.9
Tailholt C	.56	5,400	ESE	31.8	1968–71	4	23.8	16.4
Circle End	1.45	5,645	SSE	26.6	1963–71	9	14.4	7.5
Oompaul	1.16	5,225	SSW	21.1	1960–62	3	9.6	...
Hamilton	.72	5,085	S	26.8	1962	1	18.5	...

[1] The Ditch Creek watershed contains a 37-yr-old low-standard road.
[2] (Maximum elevation—minimum elevation)/2.
[3] (Total relief/length main channel to the upper ridge)100.

TABLE 2.—*Particle-size distribution of a typical Idaho Batholith soil and the corresponding settling velocities*

Description[1]	Particle size (mm)	Average composition (pct by wt)	Settling velocity[2] (mm/s)
Gravel and larger particles	>7.9	5	>500
Gravel	2.0–7.9	30	250–500
Sand	0.25–2.0	35	25–250
Do	0.075–0.25	10	5–25
Do	0.05–0.075	5	<5
Silt and clay	<0.05	15	...

[1] According to U.S. Department of Agriculture standard soil classification criteria.

[2] Settling velocities of quartz particles with shape factor=0.906 in H_2O at 20° C using Pettyjohn data (*7*).

ual watersheds varied considerably by years. As shown in table 1, standard deviations tended to vary with the means; this indicates that annual sediment yields vary more in the streams having high yields. We used a log Pearson type III frequency analysis (*3*) to develop frequency curves of annual sediment yields from the eight undisturbed watersheds for which we had 7 or more years of record (fig. 2). These curves make it possible to estimate sediment production for undisturbed watersheds for probability levels ranging from about 10 to 90 pct.

Sediment Properties

In another study initiated in 1969, we evaluated the volume weights of sediment deposited in retention reservoirs (*10*). We used a 5.0-inch-diameter by 5.0-inch-long (98.8-cubic-inch) core sampler to collect a total of 29 volume-weight samples from 7 reservoirs. In 1970, an additional 61 samples were collected from 13 reservoirs. All samples were analyzed for volume-weight and for percent organic matter by weight; in addition, particle-size distributions were determined for the 1970 samples.

The particle-size distribution data for the sediment samples are summarized in table 3. Note that the average percentages for gravel and larger particles, sand, and silt plus clay are 34.2, 64.1, and 1.7, respectively. The extremely coarse texture of the sediments is not surprising, because similar particle-size classes for soils in this area average about 35, 50, and 15 pct, respectively (table 2).

The percentage of organic matter in the sediment proved to correlate reasonably well with the sediment volume-weight (fig. 3). Organic matter content for all 90 samples averaged 5.1 pct; it ranged from less than 1 to over 60 pct for individual samples. The data suggest that organic sediments may account for a substantial loss of water-storage capacity in reservoirs on forested watersheds. These data have important ecological implications as well. For example, high levels of organic matter in reservoirs or streams may create an oxygen demand that is detrimental to aquatic life. Conversely, organic matter can play an important role in the aquatic food chain.

TABLE 3.—*Particle-size distribution of 61 sediment samples taken in 1970*

Description[1]	Particle size (mm)	Composition (pct by wt)		Composition (cumulative pct by wt)
		Average	Standard deviation	
Gravel and larger particles	>7.9	3.4	7.0	3.4
Gravel	4.75–7.9	5.3	5.8	8.7
Do	2.00–4.75	25.5	17.0	34.2
Sand	1.00–2.00	22.7	12.2	56.9
Do	0.50–1.00	16.0	9.2	72.9
Do	0.25–0.50	11.8	7.4	84.7
Do	0.075–0.25	12.6	14.1	97.3
Do	0.05–0.075	1.0	1.7	98.3
Silt and clay	<0.05	1.7	3.5	100.0

[1] According to U.S. Department of Agriculture standard soil classification criteria.

EFFECTS OF LOGGING AND ROAD CONSTRUCTION

The first study to evaluate the effects of logging and road construction on typical high-erosion-hazard lands in the Idaho Batholith was conducted between 1960 and 1967 in the Deep Creek watershed on the Payette National Forest (*11*). Sediment-retention dams were installed in eight

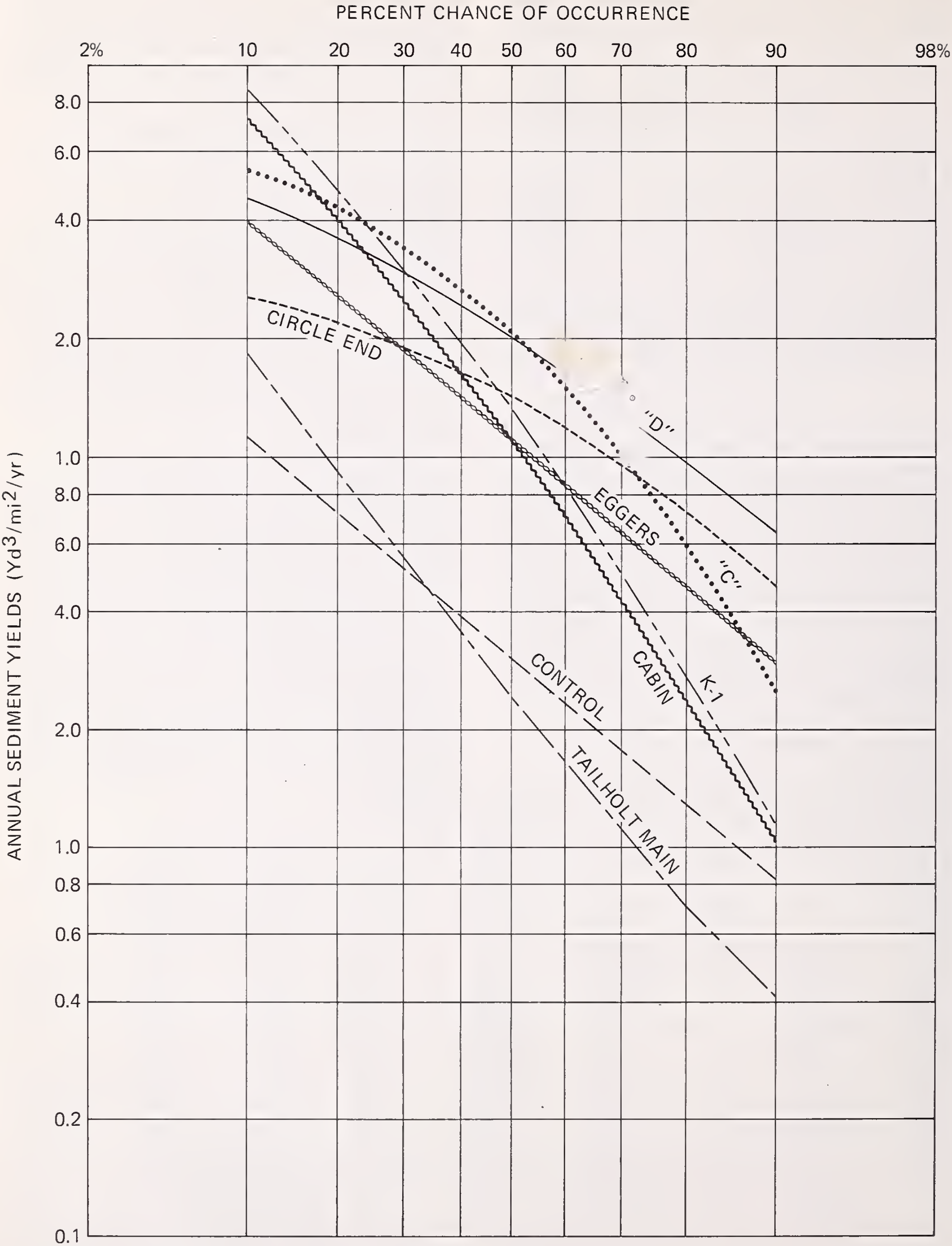

FIGURE 2.—Probability of annual sediment production on study watersheds in the Idaho Batholith.

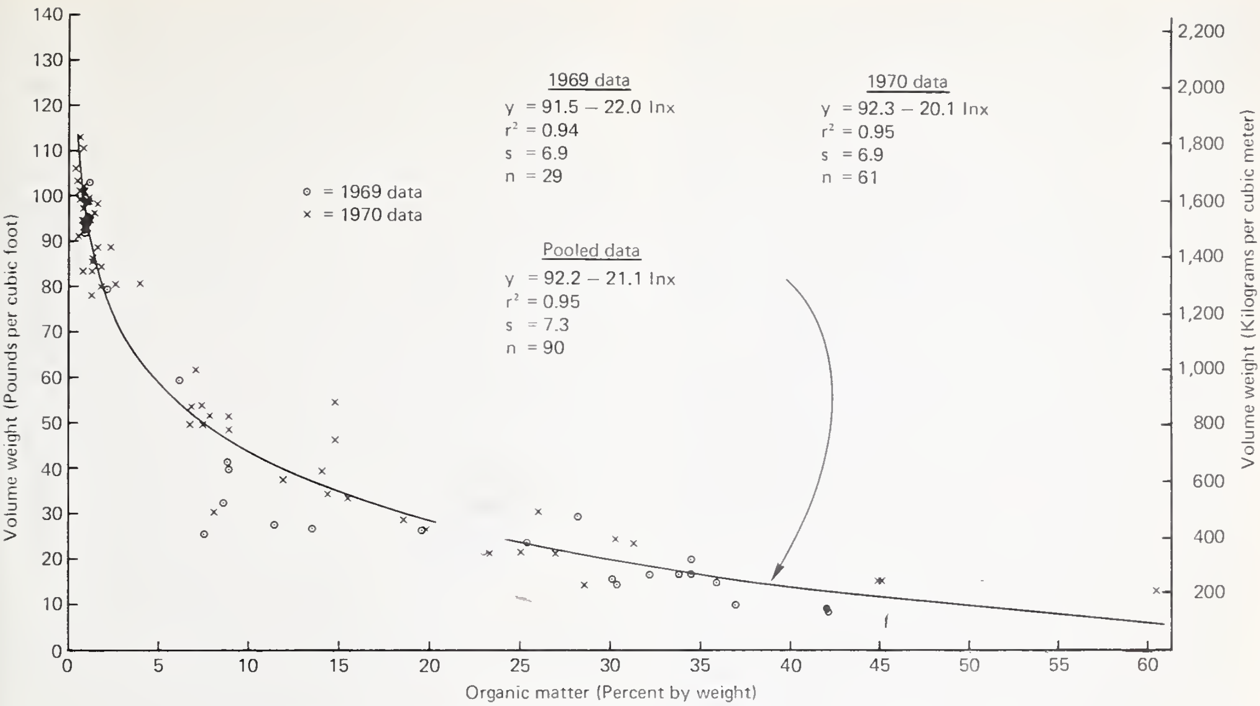

FIGURE 3.—Volume-weight of sediment as a function of organic matter.

ephemeral drainages ranging from about 1 to 5 acres in size. On five of the study watersheds (totaling 12 acres), felled trees were skidded to a truck-loading area by a skyline method; on the remaining watersheds (totaling 10 acres), felled trees were skidded with a jammer. Since the jammer cannot reach more than about 200 ft, 0.36 mi of road had to be built; thus about 20 pct of the total area of the three watersheds logged by the jammer method was disturbed by road construction. In contrast, no roads were constructed on the watersheds logged with the skyline method.

Erosion plots located within the logged areas showed no statistical difference in erosion resulting from the two skidding systems. For the 6-yr study period, sediment yields (expressed per unit of area subjected to only tree felling and log skidding) averaged about 1.6 times as great as sediment yields from nearby undisturbed watersheds. Sediment produced by surface erosion from roads (expressed per unit of area disturbed by road construction) averaged 220 times as great as yields produced from nearby undisturbed lands for the same study period; mass erosion from roads (expressed in similar units) averaged 550 times as great. Sediment production (per unit area of the entire watershed above the sediment retention dams) equaled over 150 times the undisturbed sediment production (table 4).

Further analysis of the data dealing with sediment yields from surface erosion indicated that erosion declined very rapidly over time (fig. 4). About 84 pct of the sediment from surface erosion was produced by the end of the first year after construction. This rose to 93 pct by the end of the second year (*12*). These data are important because they indicate that erosion-control measures must be initiated as soon after road construction as possible, and that control

TABLE 4.—*Mean sediment production for a 6-yr study period on the jammer unit resulting from surface and mass erosion*

Type of disturbance	Sediment rate ($yd^3/yr/mi^2$)	Ratio to undisturbed lands
Undisturbed[1]	21	1.0
Disturbed[1]	3,193	155.2
Tree felling and log skidding[2]	33	1.6
Roads (surface erosion)[2]	4,526	220.0
Roads (mass erosion)[2]	11,316	550.0

[1] Values expressed per unit area of watershed.

[2] Values expressed per unit of area subjected to tree felling and log skidding or to road construction.

measures must exert some immediate control over erosion. (Scattering plant seed alone as was done in this study will have limited value because of the time required for seed germination and growth.)

The mass erosion occurred during a rain-on-snow event in the spring of 1965. As shown in figure 4, there appears to be no relation to the short-term time trend in surface erosion. Rather, mass erosion events occur during periods of rapid, large-volume water inputs to the soil.

Actually it is doubtful that erosion on roads in the Idaho Batholith will permanently decrease, within a reasonable time, to the level that existed before disturbance. The road tread and steep cut slopes in the Deep Creek area are composed of weathered granitic bedrock that continues to disintegrate after exposure faster than natural stabilization can take place. The material resulting from bedrock disintegraton is readily transported during subsequent runoff events. Similar bedrock conditions are found throughout much of the unglaciated portion of the Idaho Batholith.

This process is occurring on a 37-yr-old road in the Ditch Creek drainage. This 2-mi road is narrow and is closely fitted to the topography so that the lengths of cut and fill slopes are minimized. In addition, dense vegetation has developed on the fill slopes. This road represents what the casual observer would consider to be a minimum erosion hazard. Yet, note in table 1 that sediment yields in the perennial stream draining this watershed (Ditch Creek) average almost twice those from adjacent similar watersheds without roads (Eggers and Cabin Creeks). In fact, sediment yields in Ditch Creek average higher than any of the other watersheds (all without roads).

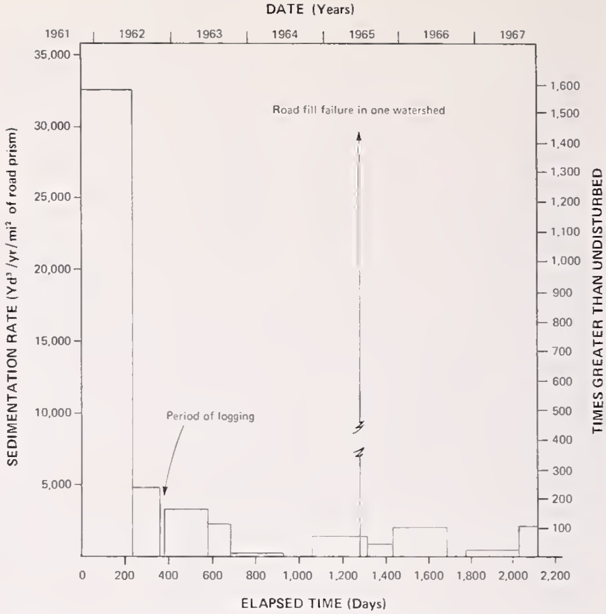

FIGURE 4.—Sediment production over time from surface erosion on jammer roads.

DOWNSTREAM EFFECTS

Sediment yields on undisturbed watersheds as well as on watersheds affected by logging activities are a concern to engineers planning downstream water-development projects. However, sedimentation takes on an added dimension in the Idaho Batholith (and possibly elsewhere) because of the high recreational values of both resident and anadromous fish. Anadromous fish have a high commercial value as well. To illustrate, the spawning beds in the Fraser River have been estimated to be worth $160,000/acre/yr (*6*).

Chapman (*4*) provides an excellent discussion of the effects of logging on fish resources in the West. He concludes that even though logging could theoretically have certain beneficial effects on fish resources, the unfortunate reality is that the effects to date have been detrimental in many streams. A primary factor causing degradation is the deleterious effect of sediment on fish in both the spawning and rearing areas of the streams. Coarse sands, which make up the bulk of the sediment produced in the Idaho Batholith, are especially damaging.

We have been engaged in a cooperative study with W. S. Platts, Forest Service fishery biologist, to evaluate trends in aquatic habitat conditions in the South Fork of the Salmon River. This 1,300-mi² drainage is a major tributary to the Salmon River; historically, it has produced Idaho's largest salmon run.

Before 1955, logging activity was limited in this area. However, such activity was accelerated in succeeding years; by 1963, it had led to a deterioration of channel conditions (*16*). During December of 1964, a large-volume rainstorm caused extensive erosion on many of the logged areas. This storm was followed by a rain-on-snow event during the spring of 1965. The resulting deposition of sand throughout much of the

river system created such concern for fishery values that the Forest Service declared a moratorium on logging and road construction in the drainage. This moratorium is still in effect.

Various studies have been implemented in the South Fork of the Salmon River to monitor changes in aquatic habitat conditions over time (*14*). Details of these studies are beyond the scope of this paper; however, a brief description of one of these studies and some of the results to date might be of interest. This study was designed to evaluate time trends in the condition of salmon spawning areas. The percentage of the streambed surface composed of various sediment-size classes was selected as an index of condition because salmon require a high percentage of gravel in the streambed to spawn successfully.

In this study, transects were located within the same reach of the Krassel spawning area each year at approximately the same location. Data were collected in late August for every year from 1966 to 1971, except for 1969, when no data were taken. Eight transects were sampled each year. The average percentages of sand and gravel on the streambed surface of the Krassel spawning area are shown by sample years on figure 5.

Linear regression analyses were used to test the statistical significance of time trends. The regression coefficients are statistically significant at the 95-pct level and indicate that sand (<4.7 mm) is decreasing at an average rate of

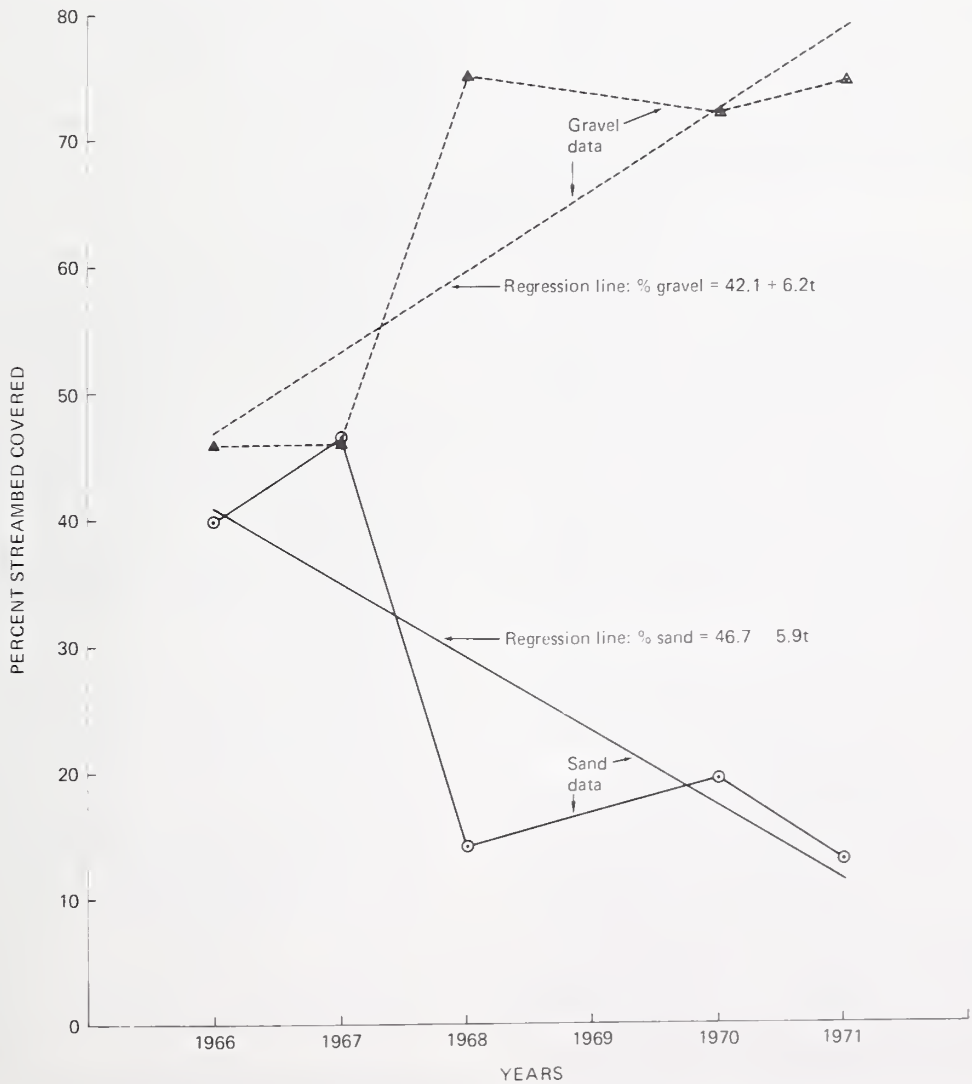

FIGURE 5.—Average percentage of sand and gravel on the streambed in the Krassel spawning area, South Fork of the Salmon River.

5.9 pct a year and that gravel (4.7–76.0 mm) is increasing at an average rate of 6.2 pct/yr (fig. 5). Similar trends were also detected in the three other key spawning areas.

The aquatic habitat conditions on the South Fork of the Salmon River are recovering rapidly since the cessation of logging in 1966. This recovery reflects the decrease in erosion with time on sediment source areas (often aided by surface erosion control measures); the lack of occurrence of extreme climatic events since 1965; the fact that mass erosion hazards have not had time to build up since 1965, when landslides occurred on areas where mass erosion hazards were high; and favorable conditions for sediment transport in the river since 1965. Apparently, before 1965 the rate of sediment recruitment to the river exceeded the rate of sediment transport by the river and sand began to aggrade in many river reaches; since 1965 the converse has occurred and degradation (as understood by sedimentationists) is taking place. Additional time trend data—surveyed channel cross sections and large-scale aerial photos of the river—confirm that degradation is occurring. The underlying spawning gravels are again exposed as the aggraded sands are removed; thus the spawning areas are approaching their predisturbance conditions.

COMPLEMENTARY STUDIES

In addition to the sedimentation studies, research is being conducted on erosion, including evaluation of average annual soil erosion in relation to site variables, effects of soil disturbance on erosion, and evaluating the effectiveness of assorted erosion-control measures. Our ultimate aim is to develop guidelines for logging practices that will permit logging and road construction on suitable lands in the Idaho Batholith without exceeding acceptable limits of onsite erosion or downstream sedimentaton damage. We feel we are well on our way toward reaching this goal.

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SEDIMENT YIELD AND SOURCE PREDICTION FOR URBANIZING AREAS

By Burton C. Becker[1] and John J. Mulhern[2]

The number one pollutant of the Nation's waters, by volume, is sediment. Annual sediment deposition in the Nation's reservoirs is estimated at approximately 850,000 acre-feet, or nearly five times the volume of earth and rock excavated for the Panama Canal. This deposited sediment preempts a water-storage capacity sufficient to provide the annual water supply for a population of 5.5 million. Not only does sediment fill stream channels, reservoirs, and estuaries, but it adds additional expense to the treatment of water supplies.

Continually changing patterns of living in the Nation have been vividly reflected in the expanding urban and suburban areas. These newly developing areas can have a sediment yield of as much as 20,000 to 40,000 times the yield from natural or undisturbed areas.

Recognizing the need for technology that could be utilized in implementing erosion- and sediment-control regulations, the Environmental Protection Agency, Office of Research and Monitoring, has funded two research projects that are concerned with developing and demonstrating this needed technology. These two projects, cost-sharing grants, are to the State of Maryland, Department of Natural Resources, and to Purdue University, Department of Agronomy. The substance of this paper is to describe these two currently ongoing projects and to briefly discuss their interrelationship.

The Joint Construction Sediment Control Project is the grant to the State of Maryland and is being conducted in the village of Long Reach, Columbia, Md. It is being operated by the Water Resources Administration, State of Maryland, under an EPA demonstration grant. Hittman Associates, Inc., of Columbia, Md., is the prime contractor to the State of Maryland for this project. Howard Research and Development Corporation, the developers of Columbia, and the Columbia Parks and Recreation Association, Inc., a nonprofit corporation representing the community, also are active contributing participants in this project.

During the period of this demonstration program, a natural and agricultural region is being converted to an urban community. This project consists of—

1. The implementation, demonstration, and evaluation of erosion-control practices.
2. The construction, operation, and demonstration of the use of a local storm-water retention pond for the control of storm-water pollution.
3. The construction, operation, and maintenance of methods for handling, drying, conditioning, and disposing of sediment.

Additionally, a gaging and sampling program is being conducted as part of this project to determine the effects of urbanization on the hydrology and water quality of natural areas.

The demonstration project is being conducted within a 190-acre watershed in the village of Long Reach. In this project area several practices are being demonstrated and evaluated in order to develop general criteria and guidelines for implementation of storm-water pollution and erosion-control techniques. Specifically, it will—

1. Evaluate the effectiveness and cost of conventional and advanced methods of erosion control in urban areas (surface landscape techniques).
2. Evaluate the effectiveness and costs of various methods for the transport, drying, conditioning, and disposal of sediment.
3. Evaluate the effectiveness and acceptability

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of introducing storm-water and sediment-retention ponds in urban communities.

One of the principal objectives of this program is the demonstration of advanced methods of erosion control in developing urban areas and evaluation of the cost and effectiveness of those methods. One of the accomplishments of this effort has been the publication entitled "Guidelines for Erosion and Sediment Control Planning and Implementation."[3] The data in this publication can be used by developers, planners, designers, engineers, and builders in the development and implementation of grading, sediment, and erosion-control plans as required by the Shore Erosion Control Act of the State of Maryland and similar laws and regulations of other States, counties, and political jurisdictions. Performance of the various erosion-control techniques demonstrated and evaluated under this program will be documented for use by regulatory agencies in the development of detailed regulations and requirements and for use in the review and approval of grading, sediment, and erosion-control plans submitted in compliance with such regulations.

Another major component of this project is the demonstration of a method of urban storm-water pollution control, using local storage and treatment of storm water. Even where the most advanced erosion-control techniques are employed, considerable erosion can be expected in watersheds undergoing urbanization. Among other sources, the stream channel itself, under the influence of the greatly increased runoff, contributes substantial quantities of sediment. The storm-water storage and treatment phase of the project is developing means to prevent this residual sediment from degrading downstream water quality.

The major objective of this phase is the demonstration and evaluation of local storage and treatment of storm water as a method of controlling storm-water pollution both during and after urbanization. In order to explore this application fully, the demonstration activities are directed to the following detailed objectives:

1. Demonstration of the use of an open pond located in the natural flood plain as a storm-water storage facility and primary sediment trap.

2. Preliminary evaluation of advanced sedimentation devices, such as tube settlers, for use as sediment traps, both alone and in conjunction with the open pond.

3. Demonstration of the use of advanced sedimentation devices, should their feasibility be determined in the preliminary evaluation.

4. Development of design criteria for the use of open ponds and advanced sedimentaton devices for control of storm-water pollution in urban areas.

5. Investigation of the effect of the open pond and other storm-water pollution-control devices on surrounding land uses and land values.

6. Investigation of the effect of storm-water pollution control and pollution-control facilities on flood plain and stream-channel ecology, both upstream and downstream.

7. Investigation of the effects of storm-water pollution control and pollution-control facilities on flood plain utilization.

One of the most important aspects of storm-water control is the handling and ultimate disposal of sediment. The most efficient sediment-retention system can be rendered useless if the collected sediment is merely transferred to another area in such a manner as to allow its reentry into surface waters. Sediment handling and disposal is difficult and costly. Sediment, as such, has little economic value, so that there is considerable incentive for the employment of low-cost, yet effective, disposal techniques.

The objectives of the sediment-handling, drying, conditioning, and disposal phase of the study are—

1. Evaluation and demonstration of various means of removing sediment from each of the sediment-collection systems.

2. Evaluation and demonstration of techniques for transporting wet sediment from the collection systems to the drying facility.

3. Evaluation and demonstration of techniques for conditioning sediment before application to drying beds.

4. Evaluation and demonstration of methods for efficient drying of sediment.

5. Evaluation and demonstration of methods for ultimate disposal of sediment, including organic and inorganic additives to alter sediment properties.

[3] U.S. Environmental Protection Agency. 1972. Guidelines for erosion and sediment control planning and implementation. EPA–R2–72–015. Superintendent of Documents, Washington, D.C. 20402.

The hydrology and laboratory analysis phase of the demonstration project has been planned to coordinate and simplify the collection and analysis of data relating to rainfall, streamflow, water quality, flood-plain ecology, etc. A comprehensive hydrology and water-quality monitoring program is being conducted. It uses three rain gages and four stream-gage and water-sampling installations. Locations are shown in figure 1.

The three permanent rain-gaging stations employ weighing-bucket, continuous-recording gages. Two of the gages are Belfort Instrument Company[4] products with spring-wound clock drives and ink-pen recorders. The third is a Fisher-Porter punch-tape model powered by a 7½-V dry cell.

Two of the stream-gaging and sampling stations have been built at the junction of the tributaries draining the reference and experimental subwatersheds. They were located so that differ-

[4] The mention of trade names or commercial products does not constitute endorsement or recommendation for use by the Environmental Protection Agency.

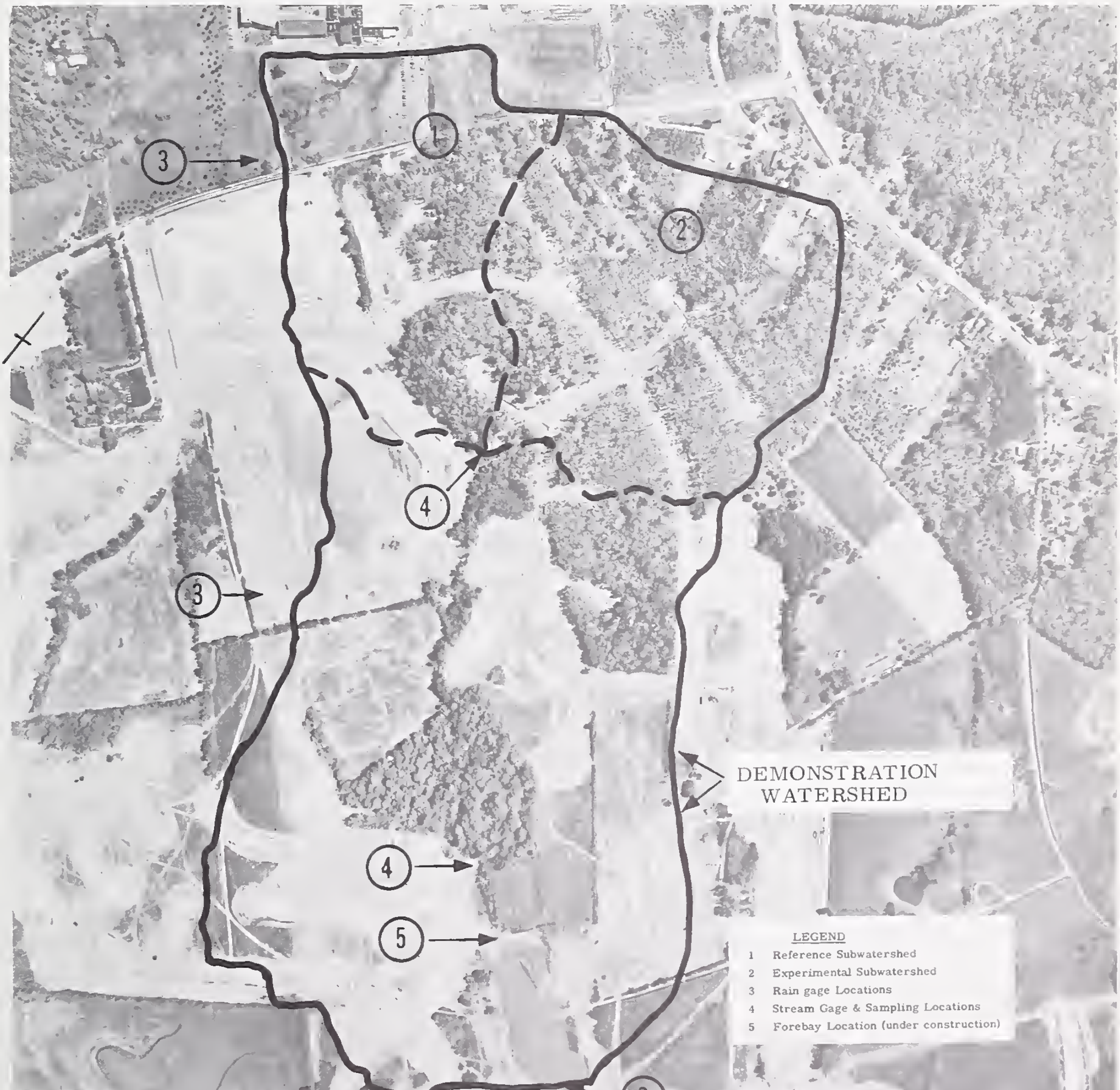

FIGURE 1.—Demonstration watershed and subwatershed locations.

ences in the runoff and suspended solids produced in the experimental subwatershed, where advanced erosion-control practices were applied, could be compared to the reference subwatershed, where only minimal practices were required. Two other gaging and sampling stations were established immediately upstream and immediately downstream from the 4-acre pond.

The tandem stream gages (farthest upstream) are precalibrated, broadcrested, V-notch weirs developed and tested by the U.S. Department of Agriculture. The concrete weir caps have 2:1 side slopes and were poured and formed directly on steel sheet piles driven a minimum of 6 ft below the elevation of the stream channel. Earth berms extend from the end of the weir caps to the limit of the calculated 50-yr, post-development flood plain.

The stilling wells and shelters contain both the sediment-monitoring equipment and a Stevens duplex water-level recorder, type 2A35, which can simultaneously measure and record the water levels going over weirs 1 and 2.

Station 3, just above the pond and forebay, is a weir similar to those at stations 1 and 2, except the side slopes of the weir cap are at 3:1. This station is also served by a Stevens type A35 water-level recorder.

Station 4, below the pond, uses a sharp-crested, compound, 90° V-notch and rectangular weir as a control section. The V-notch is 10 inches high and the rectangular section is 2½ ft high by 6 ft wide. The damping effect of the principal spillway facilitates the use of this small installation. The stilling well is equipped with a Belfort portable liquid-level recorder.

When necessary, additional stream gaging is performed using a Gurley pygmy current meter. To date, this method has been used primarily to check the calibration of the permanently installed weirs.

An automatic water-sampling station is located at each of the four permanent stream-gaging sites. The samples collected from these automatic stations are supplemented by depth-integrated hand samples.

At sites 1 and 2, the sampling equipment is housed in a combined instrumentation and stilling well shelter. Approximately 13 ft upstream from each weir, the intake from a ¼-hp pump provides sample water which flows through a turbidimeter and then through a fluidic sample bottle rack which periodically diverts the flow into a sample bottle. The turbidimeters are equipped with Rustrak recorders as well as visual observation equipment. At the present time, the fluidic samplers are programed to sample every half hour. A mercury switch automatically starts each pump and turbidimeter recorder at a given water stage and cuts off after the stage falls below the predetermined level.

The automatic sediment-monitoring equipment at site 3 (upstream from the pond) consists of a PS-67 pumping sampler. The intake for the sampler is located in the stream, some 15 ft upstream from the weir. The pumping sampler is fed by a ¼-hp pump which utilizes a 36-V, d.c. power supply. An automatic switch activates the sampler upon a sufficient rise in stream water level and stops it when the stage falls below the set level. The sampler can be set to take samples at virtually any time increment. It is now set to sample every 15 min when activated.

The automatic sampling equipment at site 4, below the pond, is a Serco single-stage vacuum sampler. A switch activates the sampler upon a sufficient rise in stream level, and 24 continuous samples are then taken at equal specified time intervals.

The primary purpose of the gaging, monitoring, and sampling program is to establish storm runoff volumes and gross sediment yields. The storm runoff is, in turn, related to the intensity and duration of the rainfall, land use, and ambient field conditions. As the area becomes more developed, the total volume of runoff for a given storm would, naturally, increase because of the larger amount of impervious area. Sediment volumes should, however, decrease as the area becomes stabilized.

Reservoir and stream-channel sedimentation surveys are conducted at 3-month intervals as a check on the sedimentation data provided by the gaging and sampling stations.

The Joint Construction Sediment Control Project's first major publication, "Guidelines for Erosion and Sediment Control Planning and Implementation," is intended primarily to help those responsible for, or engaged in, urban construction to prevent the uncontrolled movement of soil and the subsequent damage it causes. This report and the documents to follow from this project, along with work currently being conducted under an EPA grant to Purdue Univer-

sity, should provide much-needed technology for minimizing erosion and sediment pollution.

Environmental Protection Agency project 15030 HIX, Erodibility of Urban and Suburban Construction Site Subsoils as Predicted by Chemical, Mineralogical, and Physical Parameters, is a grant to Purdue University's Department of Agronomy. The project is to refine the erodibility equation, previously developed for surface soils, for use on the subsoils commonly found at construction sites. This will be accomplished by—

1. Using a "rainulator" (rainfall simulator) to test the soil erodibility model on heavier textured soils commonly found at construction sites.
2. Relating various chemical, mineralogical, and physical properties of selected surface and subsurface soils to their erodibility factor (K), previously determined by field experimentation.
3. To arrive at an equation, using data obtained in 1 and 2, which can be used by erosion-control investigators to predict soil losses at construction sites more accurately.

From a review of the available technology for erosion and sediment control from construction activities, it was concluded that a more accurate erodibility-prediction tool was needed, so that better erosion- and sediment-control measures could be planned and implemented for construction sites. This prediction mechanism combined with the erosion- and sediment-control procedures developed and demonstrated at Columbia, Md., should make it possible to implement a more viable sediment control program.

The detachment of soil particles by rainfall and surface water flows are primary processes in soil erosion. Detached particles can be transported by the runoff waters, and thus become a major pollutant of the Nation's waters. By determining the chemical, physical, and mineralogical factors that influence soil erosion by water, it is possible to develop or modify the universal soil loss equation for use on subsoils.

The universal soil loss equation is widely used by many individuals and governmental agencies as a guide in drawing up recommendations based on "soil-loss tolerances." The primary consideration of those recommendations is the maintenance of a high level of economic productivity for an unspecified period of time. The principal factors considered for this equation are those that influence surface soil erosion, such as rainfall, soil erodibility, slope length, slope gradient, cropping management, and erosion-control practices. Attempts to predict the erodibility of subsoils commonly found at construction sites have demonstrated that the subsoils do not always behave as predicted by the universal soil loss equation.

The most difficult parameter to specify for the universal soil loss equation is the soil-erodibility factor. Wischmeier and Mannering[5] correlated (statistically) the erodibility factor of some 55 selected Corn Belt soils to an array of 24 soil parameters, primarily soil physical properties, and not including chemical and mineralogical properties. Since the development of this regression equation, Wischmeier has sought to simplify it to a more workable relationship. The result has been the development of a two-section nomograph from which the soil-erodibility factor can be read, if the following four major soil parameters are known: organic matter content; permeability; soil structure; and a newly derived particle-size-distribution term.[6] Although the predictive accuracy of this erodibility nomograph appears to be good for the range of soils encompassed by the data analyzed, its applicability to heavier textured soils, usually found as subsoils, is still being examined. The soil parameters used in developing the relationships were mainly physical in nature, whereas the actual cohesion between soil particles, i.e., interparticle bonding, is influenced by chemical and mineralogical properties in the soil material. Therefore, existing relationships for predicting soil erosion can be improved by including factors for soil chemical and mineralogical makeup.

The major chemical and mineralogical parameters responsible for soil stability are thought to be organic matter, clay content, clay type, free iron oxide, silicates, free aluminum oxide, and the valency of the ionic constituents in the soil-adsorption complex. It is anticipated that when the relationship between soil erosion and the chemical and mineralogical parameters of soils has been determined, results from simple physical, chemical, and mineralogical determinations

[5] Wischmeier, W. H., and Mannering, J. V. 1969. Relation of soil properties to its erodibility. Soil Science Society of America Proceedings 33: 131–137.

[6] Wischmeier, W. H. 1971. A soil erodibility nomograph for farmland and construction sites. Journal of Soil and Water Conservation 26(5): 189–193.

of appropriate soil constituents can be used to obtain a more accurate prediction of anticipated soil losses at construction sites, so that control measures can be recommended to minimize erosion and sediment pollution.

The research project at Purdue has the following objectives:

1. To test, by the use of a rainulator on field plots, the newly developed erodibility model (derived from light-textured surface soils) on some heavy-textured soils, commonly found as subsoils at construction sites.

2. To relate various chemical and mineralogical properties of selected surface and subsurface soils to their erodibiilty factor (K) which has previously been determined through field experimentation.

3. To attempt to arrive at a regression equation or a modified nomograph with data from 1 and 2, for use by erosion-control investigators, so that they can predict anticipated soil losses at proposed construction sites more accurately.

This project was completed in June 1973. Data collection and interpretation are still in progress.

Preliminary evidence, however, supports the thesis that subsoils do not necessarily behave as predicted by the universal soil loss equation. The information being gathered by the project should provide a better means of predicting subsoil losses for proposed construction sites.

The combined results from the Maryland project and the Purdue project should vastly improve erosion- and sediment-control technology for construction sites. While they represent only a beginning, the information obtained from the projects, and the Maryland demonstration in particular, should greatly advance the state of the art of sediment control during the transformation of rural and natural areas into urban and suburban areas.

SEDIMENT YIELDS RELATED TO CHARACTERISTICS OF TWO ADJACENT WATERSHEDS[1]

By A. J. Bowie, G. C. Bolton, and J. A. Spraberry[2]

INTRODUCTION

Runoff, sediment, and supplemental data from two adjacent watersheds in northern Mississippi have been evaluated. These two watersheds are part of a comprehensive study of sediment yield that is designed to define the processes of erosion and the relative effect of sedimentation on land and water resources.

The ultimate objective of this study is to develop methodology for predicting sediment yield and transport rates in complex watersheds, varying in size from a few acres to several square miles. The primary objectives of the studies are (1) to determine sediment yields by systematic sampling and measuring of storm flows at a streamflow gaging station in each watershed, (2) to delineate and establish the relative significance of sediment sources on sediment yield, and (3) to relate measured sediment yield to calculated gross erosion and watershed characteristics.

Both watersheds were instrumented for runoff and sediment yield measurements in November 1956, with actual data collection beginning in January 1957. Measured runoff and sediment data used in this report are for 14 yr (water years 1958–71). Land-use surveys and computation of gross erosion were made periodically from 1958 to 1972.

EXPERIMENTAL AREA

The two watersheds discussed in this report are part of 117-mi² experimental watershed located in the upper portion of the Pigeon Roost Creek basin in northern Mississippi. The two watersheds, joined by a common boundary approximately 1.0 mi long, are shown in figure 1 as numbers 4 and 5. Watershed 4 has a drainage area of 1,580 acres and watershed 5 is established as 1,000 acres.[3]

The standard instrumentation at each of two gaging sites consists of a Stevens type A continuous water-level recorder installed in a wooden shelter over a 24-inch corrugated iron pipe well. Automatic suspended-sediment pumping samplers were installed at each gaging site. These samplers are designed to collect and store samples at selected intervals throughout the hydrograph when the water in the stream reaches a preselected stage (*7, 9*).[4] Footbridges across the stream channels at selected cross sections are used to support a traversable streamflow sampler. Locations of the recording rain gages and streamflow gaging stations are shown in figure 2. The gaging stations are located in defined channels at the lower end of each watershed (*4*).

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[1] Cooperative research of the Agricultural Research Service, U.S. Department of Agriculture, and the Mississippi Agricultural Experiment Station and the University of Mississippi.

[2] Research hydraulic engineer, mathematician, and soil scientist, respectively, USDA Sedimentation Laboratory, Southern Region, Agricultural Research Service, Oxford, Miss. 38655.

[3] Watershed 4 drainage area adjusted on Jan. 1, 1965, from 2,000 to 1,580 acres. Watershed 5 drainage area adjusted on Oct. 1, 1969, from 1,130 to 1,000 acres.

[4] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this paper.

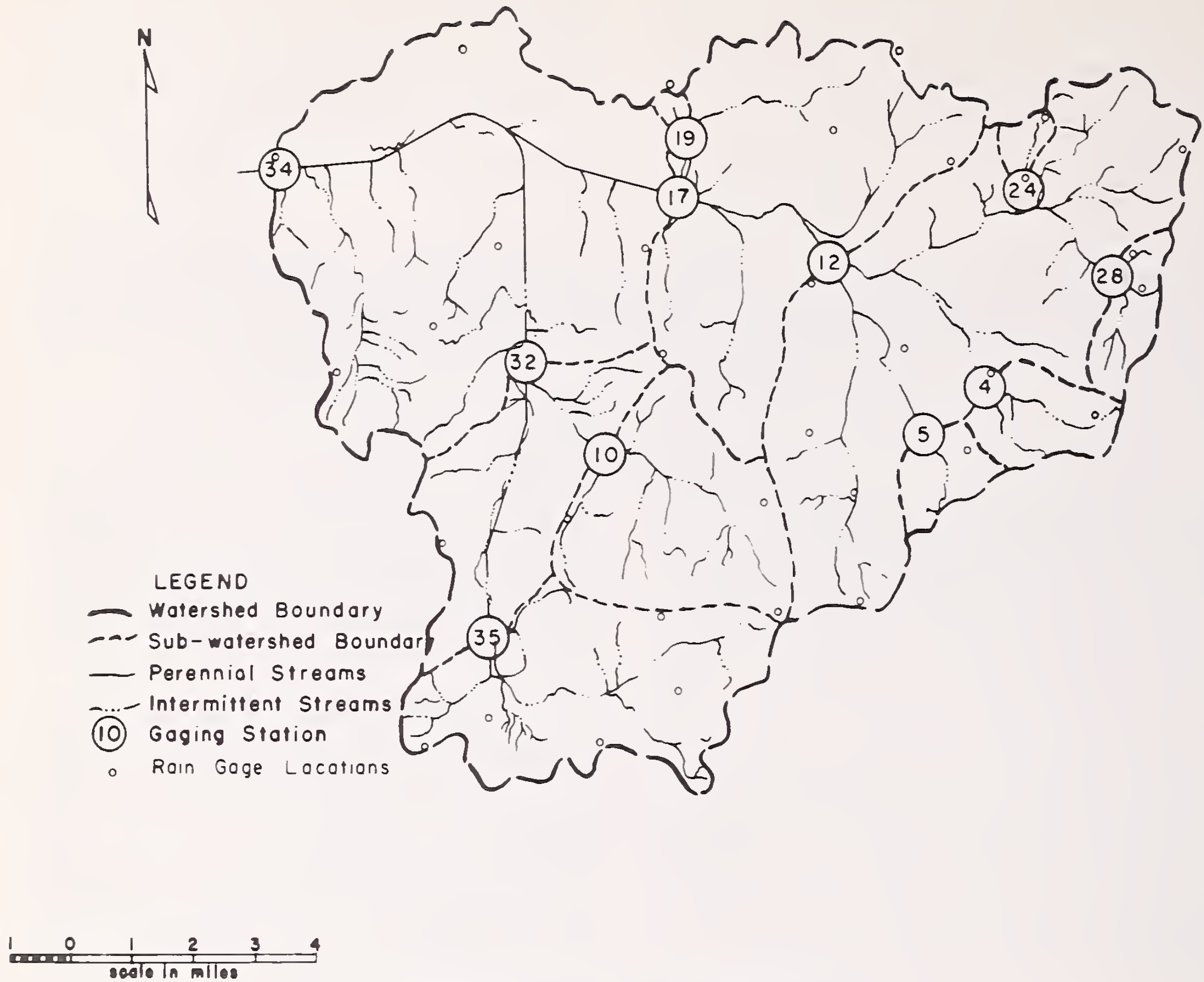

FIGURE 1.—Pigeon Roost Creek watershed.

GENERAL CHARACTERISTICS

Topography

Both watersheds have rather narrow, flat, flood plains with natural channels and dissected upland areas. The major flood plain in watershed 4 is approximately 2.0 mi long and 0.15 mi wide; in watershed 5 it is 0.8 mi long and 0.08 mi wide (*3*). The channels have few straight reaches, and most have banks that scour easily. The average channel width-depth ratio is 3:1 at gaging station 4 and 2:1 at gaging station 5. The average slope of the main channel for both watersheds is approximately 4.5 pct. The drainage density is 1.60 mi/mi^2 for watershed 4 and 1.14 mi/mi^2 for watershed 5. Watershed 4 has a mean slope of 10.4 pct; watershed 5 has 9.0 pct.

Geology

There are three major geological formations in both watersheds, the Kosciusko, Tallahatta, and Meridian (*1*). The texture of the formations is predominantly sands with local clay lenses. The Meridian formation underlies the entire area of both watersheds. There are no surface outcrops of this formation within the watershed boundaries. There are outcrops of Kosciusko and Tallahatta in both watersheds. A relatively impermeable clay lense underlies the valley fill in watershed 5. A clay seal is also present beneath watershed 4, but it does not appear to be continuous. There is a smaller percentage of the Kosciusko formation, and a smaller percentage of the

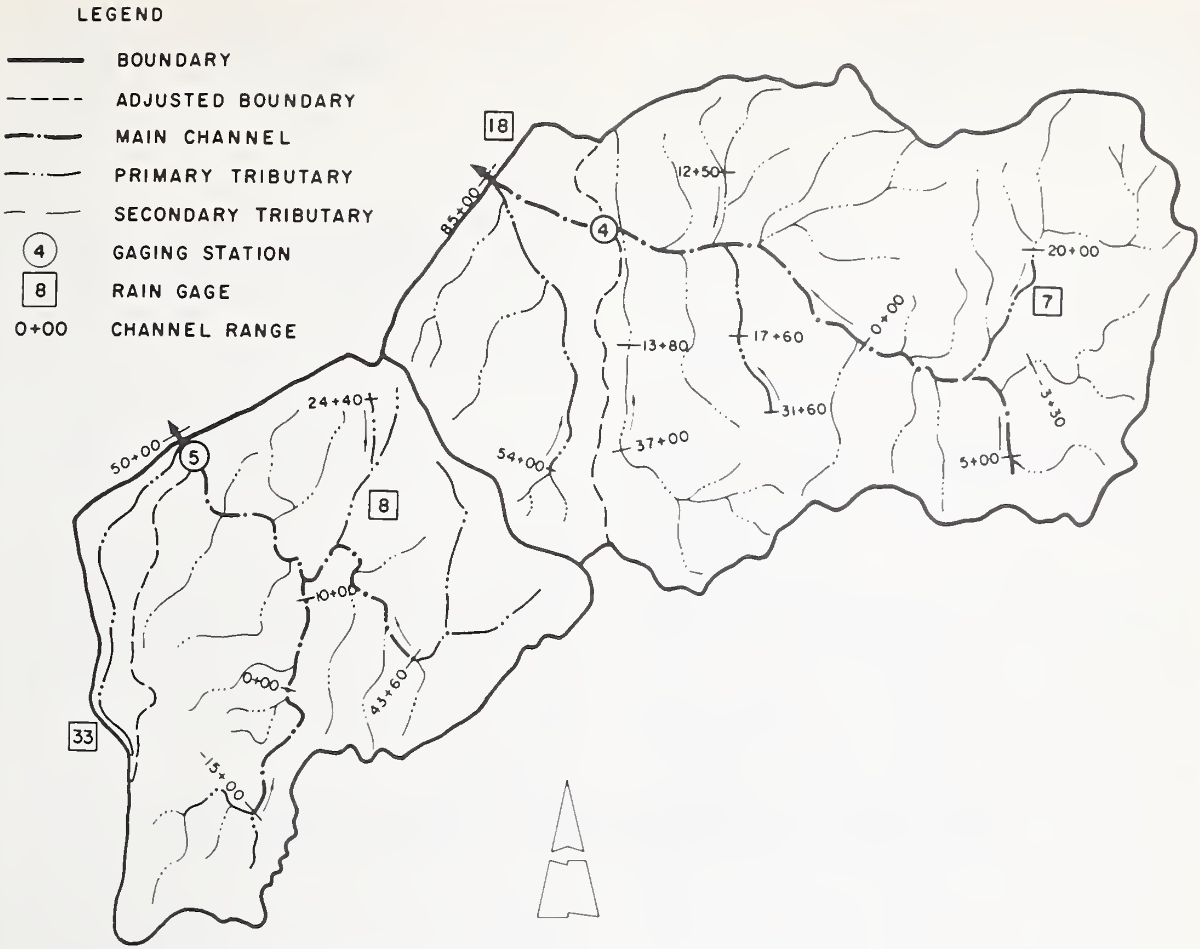

FIGURE 2.—Watersheds 4 and 5, Pigeon Roost Creek Basin, Marshall County, Miss.

exposed Tallahatta formation. Compared with the Tallahatta, the Kosciusko has a lower permeability because of more even dissemination of clay throughout the formation.

Soils

The soils of the watersheds were developed from thin loess of silty material, which overlies various kinds of coastal-plain material. These soils have been classified by external and internal characteristics according to series and type (*3*). The three principal soil types within the series are fine sandy loam, sandy loam, and silt loam.

The soils have been further classified according to the Soil Conservation Service scheme for hydrologic grouping (*12*). Soil properties that influence runoff can be represented by a hydrologic parameter: the minimum rate of infiltration into a bare soil after prolonged wetting. This parameter is the qualitative basis of the classification of soils into four major hydrologic soil groups. There are two hydrologic soil groups in watersheds 4 and 5. The two groups are

B. Mostly sandy soil having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse texture. These soils have a moderate rate of water transmission.

C. Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately

fine to fine texture. These soils have a slow rate of water transmission.

The proportionate extent of the hydrologic groups, in percent, is as follows:

Watershed	*Hydrologic soil group B, coastal-plain (sandy) material*	*Hydrologic soil group C, loess (silty) material*
4	72	28
5	44	56

SEDIMENT YIELDS

Annual Thiessen-weighted precipitation during the period of record varied only slightly, with maximum amounts alternating between the two watersheds (table 1). Watershed 5 had 693.4 inches of accumulated rainfall; watershed 4, 681.6 inches.

Generally accepted methods and procedures were used to measure flow and to obtain sediment samples at each gaging station; specifically, standard Geological Survey procedures were used for velocity measurements, and the depth-integrated equal-transit-rate method was used to collect samples of the water-sediment mixture (*4, 7*). In addition, supplementary samples were collected with the automatic pumping samplers beginning with the 1971 water year. Runoff was determined from continuous water-stage information and current meter measurements.

A comparison of the annual weighted concentration of sediment in discharge is shown in figure 3. The higher concentration came from watershed 5 in 7 out of 14 yr. Concentrations during 2 yr were almost equal. The maximum deviation from equal value was 1,040 p/m (*3*). The mean annual concentration was 5,305 p/m for watershed 5 and 5,202 p/m for watershed 4.

Annual runoff and sediment yields were consistently higher for watershed 5 (table 1). As would be expected from the difference in annual yield, the accumulated yield is considerably higher for watershed 5 than for watershed 4. The total accumulated runoff and sediment yield for watershed 5 exceeded those for watershed 4 by 84.2 inches and approximately 50 tons/acre, respectively.

METHOD OF COMPUTING GROSS EROSION

Erosion is usually classified according to the eroding agent (wind, water, rain-splash) and type (sheet and rill, gully, channel). Sheet erosion involves the removal of a thin layer of the land surface over an extensive area and is usually not visible to the eye. This type of erosion becomes evident by the formation of rills. It has been estimated that soil loss from rill erosion can be seen if it amounts to about 5 tons or more per acre. This is equivalent in volume to approximately 2 acre-feet/mi^2 (*13*). Three types of erosion occur in the watersheds; these are sheet and rill, gully, and channel, with water as the entraining agent and prime mover of the eroded materials.

Land use surveys were begun in the watersheds in 1957 and have continued to the present time (*10*). Considerable effort was made to evaluate the contribution of sediment from all sources and to differentiate between the various sources areas. Land use and cover conditions, the percent and length of slope, the area of active gully erosion and the location of sediment-detention structures and gully plugs were mapped on aerial photographs. When this information was verified in the field, the annual erosion was computed separately for each delineated source area and added to give total watershed erosion.

In calculating annual gross erosion, the quantity of material derived from sheet erosion and the quantity contributed by gully erosion were computed separately. Relative erosion factors were assigned to each delineated area, and the sheet erosion was calculated for the total area using the universal soil loss equation (*14*). Gully erosion was calculated with the "2-inch gully rate" developed by Woodburn (*15, 16*). The Woodburn method was further substantiated in a study conducted by Miller et al. (*8*).

RESULTS AND DISCUSSION

Although weighted precipitation was nearly equal, table 1 shows that average runoff from watershed 5 exceeded that from watershed 4 by more than 100 percent. The average sediment yields for the two areas are in the same proportion, with 6.70 tons/acre for watershed 5 and 3.13 tons/acre/yr for watershed 4. The sediment concentration for both watersheds was approxi-

TABLE 1.—*Summary of precipitation, runoff, and sediment yields for watersheds 4 and 5, Pigeon Roost Creek basin*

Water year	Weighted rainfall by Thiessen method (in)		Runoff (inches)		Sediment yield (tons/acre)		Sediment yield, (tons/acre) /inch runoff	
	Watershed 4	Watershed 5	Watershed 4	Watershed 5	Watershed 4	Watershed 5	Watershed 4	Watershed 5
1958	60.02	57.05	6.07	11.46	4.13	6.66	0.68	0.58
1959	42.14	42.19	2.76	6.82	2.43	5.31	.88	.78
1960	41.97	42.03	3.11	7.11	1.39	4.08	.45	.57
1961	48.81	48.72	4.14	9.47	2.41	5.87	.58	.62
1962	59.13	60.75	8.55	15.05	5.58	8.37	.65	.56
1963	35.00	36.18	1.28	3.42	1.08	2.38	.84	.70
1964	53.72	55.00	7.00	14.27	4.83	9.86	.69	.69
1965	49.73	53.77	9.32	18.08	5.50	10.35	.59	.57
1966	34.96	35.43	2.56	6.83	1.56	4.45	.61	.65
1967	45.34	47.80	3.93	9.68	2.46	6.99	.63	.72
1968	52.85	53.97	6.23	12.43	2.60	6.71	.42	.54
1969	60.13	60.25	10.11	19.09	4.99	10.51	.49	.55
1970	53.40	53.01	6.88	17.18	2.70	7.40	.39	.43
1971	44.40	47.22	3.83	9.08	2.13	4.85	.56	.53
Accumulated	681.60	693.37	75.77	159.97	43.79	93.79	...	...
Average	48.69	49.53	5.41	11.43	3.13	6.70	.58	.59

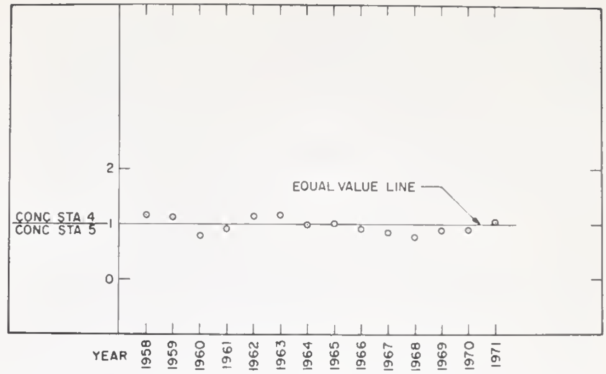

FIGURE 3.—Comparison of weighted discharge concentrations, watersheds 4 and 5.

mately equal, as indicated by figure 3. Sediment yield per inch of runoff was essentially the same, as shown in table 1.

In a previous study by Bowie and Bolton on the variations of runoff in the watersheds (*3*), it was found that certain parameters and hydrologic factors were almost identical or had insignificant variances. It was concluded that these parameters and hydrological factors—precipitation, drainage density, compactness coefficient, average slope of streams, land slope, and slope length—did not contribute to the difference in runoff.

Although the watersheds are separated by a common boundary of only 1.0 mi, as shown in figure 2, geology and soils differ significantly. These two factors are considered to be the major contributors to the difference in runoff. For example, in watershed 5 there is a smaller percentage of recent deposits or valley alluvium, a higher percentage of the less permeable Kosciusko formation, and a smaller percentage of the more permeable, exposed Tallahatta formation.

Proportions of the three geologic formations in each watershed are as follows (in percent):

Watershed	*Kosciusko formation*	*Tallahatta formation*	*Valley alluvium*
4	64	29	7
5	88	10	2

Classified by hydrologic soil group, watershed 4 has a higher percentage of the better drained group B sandy materials and a lower percentage of the group C fine-textured silty material. The wider alluvial bottoms of watershed 4 are surrounded by diversion ditches dug in deep sandy material. The narrow alluvial bottoms of watershed 5 are confined to the lower reaches and are not protected by diversions.

Six complete land-use surveys were made on each of the two watersheds from 1957 to 1972. A summary of these surveys is given in tables 2 and 3. Annually, there was relatively little difference in the percentage of total contributing area between the watersheds. Land use, in some cases, did change considerably during the study period (figs. 4 and 5). The greater change occurred during the early period of record, with a substantial reduction in cultivated land in each watershed. Probably the most important change was the 22-pct increase of the total area in watershed 4 in pasture and 13-pct increase in forest, with each classified as good cover. The overall change for the period of record (1957–72) can be summarized as follows:

Land use	*Watershed 4*	*Watershed 5*
Cultivation	8% reduction	5% increase.
Pasture	22% increase	4% reduction.
Idle	25% reduction	8% reduction.
Forest	13% increase	7% increase.
Gully	1% reduction	0.9% reduction.

In most cases, the annual change in land use is reflected in the computations of gross erosion given in table 4. As stated previously, the annual erosion was computed separately for each delineated area and added to give total watershed erosion.

If appraisal of sediment source areas in a watershed were made by a single reconnaissance survey, it is possible that a very important contributor to sediment yield could be underestimated or in some cases overlooked entirely. It is a misconception to think that the only significant eroded material that is transported in a stream channel during storm runoff originates entirely from land surfaces within the drainage area. The erosion that occurs within the channel system, which includes streambed and streambank, can be very significant under some circumstances. This is especially true if the channel bank and bed is composed largely of unconsolidated material.

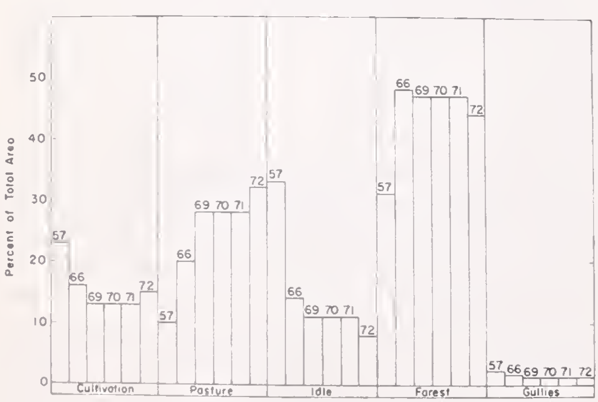

FIGURE 4.—Changes in land use for watershed 4, 1957–72. Years are given above the bars.

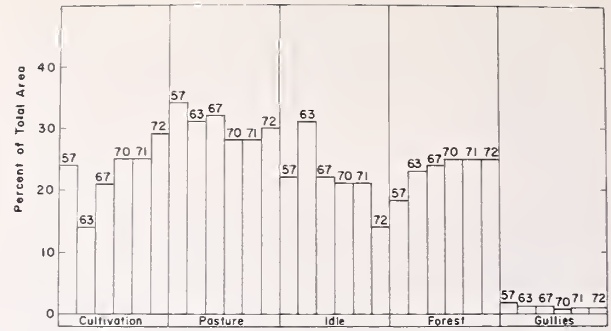

FIGURE 5.—Changes in land use for watershed 5, 1957–72. Years are given above the bars.

It has been estimated that some 300,000 mi of streambank in the United States produce about 500 million tons of sediment each year (*2*). This amounts to approximately 0.32 tons/lin ft of channel. The importance of channel contribution to total sediment yield was recognized in watersheds 4 and 5 at the time the studies were initiated. Quantitative estimates of channel erosion rates were obtained from cross-section surveys made at 5-yr intervals (figs. 6 and 7). Surveys were made on approximately 3.5 mi of permanent, well-defined channels in watershed 4 and on 2.6 mi of permanent, well-defined channels in watershed 5 (figs. 8 and 9).

Computation of sediment yield for the channels was based on an estimated in situ unit weight of 90 lb/ft^3 for the eroded material. As shown in table 5, 40 pct of the average annual sediment yield from watershed 4 and 16 pct from watershed 5 are computed as channel erosion. The difference in channel contribution between the two watersheds can be attributed partly to land use. The reduction in cultivated land combined with a large increase in good-to-excellent cover conditions in watershed 4 helped to reduce the amount of eroded material reaching the channel system; whereas, an increase in cultivated land with a reduction in permanent cover contributed to conditions in watershed 5 that provided for more eroded material reaching the channel system. The increased amount of overland eroded material reaching the channel system in watershed 5 probably decreased propor-

TABLE 2.—*Summary of land use for watershed 4, 1957–72*[1]

Land use	C acres	NC acres	Pct of total area C	Pct of total area NC	C acres	NC acres	Pct of total area C	Pct of total area NC	C acres	NC acres	Pct of total area C	Pct of total area NC
	1957				1966				1969			
Cultivation	386	83	19	4	189	59	12	4	138	61	9	4
Pasture	161	49	8	2	158	165	10	10	258	188	16	12
Idle	475	185	24	9	159	67	10	4	132	43	8	3
Forest	442	177	22	9	535	223	34	14	584	159	37	10
Gully	16	26	.8	1.3	9	16	.6	1	11	6	.7	.4
Total	1,480	520	74	26	1,050	530	66	34	1,123	457	71	29
	1970				1971				1972			
Cultivation	138	61	9	4	138	56	9	4	187	44	12	3
Pasture	258	188	16	12	275	176	17	11	254	252	16	16
Idle	132	43	8	3	132	45	8	3	65	58	4	4
Forest	584	159	37	10	587	155	37	10	545	157	34	10
Gully	11	6	.7	.4	10	6	.7	.4	10	8	.6	.5
Total	1,123	457	71	29	1,142	438	72	28	1,061	519	67	33

C Part of total watershed contributing to downstream sediment yield. NC Part of total watershed not contributing to downstream sediment yield.

[1] Watershed area adjusted on Jan. 1, 1965, from 2,000 to 1,580 acres.

TABLE 3.—*Summary of land use for watershed 5, 1957–72*

Land use	C acres	NC acres	Pct of total area C	Pct of total area NC	C acres	NC acres	Pct of total area C	Pct of total area NC	C acres	NC acres	Pct of total area C	Pct of total area NC
	1957				1963				1967			
Cultivation	225	44	20	4	112	41	10	4	180	53	16	5
Pasture	282	101	25	9	171	182	15	16	193	172	17	15
Idle	210	33	19	3	224	125	20	11	187	58	17	5
Forest	209	5	18	.4	238	22	21	2	237	35	21	3
Gully	10	11	.9	1.0	5	10	.4	.9	7	8	.6	.7
Total	936	194	83	17	750	380	66	34	804	326	71	29
	1970				1971				1972			
Cultivation	196	85	17	8	196	85	17	8	228	104	20	9
Pasture	177	139	16	12	177	139	16	12	205	139	18	12
Idle	166	65	15	6	166	65	15	6	111	40	10	4
Forest	253	38	22	3	253	38	22	3	254	38	22	3
Gully	6	5	.5	.4	6	5	.6	.4	6	5	.6	.4
Total	798	332	71	29	798	332	71	29	804	326	71	29

C Part of total watershed contributing to downstream sediment yield. NC Part of total watershed not contributing to downstream sediment yield.

TABLE 4.—*Computed gross-erosion and sediment-delivery ratios*

Watershed and year	Gross erosion (tons/acre)		Delivery ratio[1]	
	C area	Total area	Pct	Adjusted[2]
Watershed 4:				
1957	20.2	23.4	33	19
1966	11.8	14.0	13	8
1969	9.4	13.3	51	27
1970	7.1	8.2	38	16
1971	7.1	8.2	30	18
1972	8.0	8.3	..	..
Watershed 5:				
1957	16.5	19.5	61	52
1963	11.7	14.3	20	18
1967	13.3	14.1	53	46
1970	12.2	13.1	61	48
1971	12.2	13.1	40	33
1972	15.1	17.9	..	..

C Contributing area.
[1] Delivery ratio computed for contributing area only.
[2] Delivery ratio adjusted for channel erosion.

TABLE 5.—*Channel erosion, 1957–72*

Explanation	Watershed 4, 1,580 acres[1]	Watershed 5, 1,000 acres[2]
Total length of channels surveyed ....ft....	18,500	13,550
Total sediment yield[3] ....tons....	35,299	17,731
Average annual yield per linear foot of channel ....ton....	0.127	0.087
Average annual yield per acre[4] ....tons....	1.24	1.05
Channel contribution to average annual sediment yield[5] ....pct....	40	16

[1] Watershed area adjusted on Jan. 1, 1965, from 2,000 to 1,580 acres.
[2] Watershed area adjusted on Oct. 1, 1969, from 1,130 to 1,000 acres.
[3] Based on an estimated in situ unit weight of 90 lb/ft³ for the eroded material.
[4] Adjusted for change in drainage area.
[5] 14-year average sediment yield (tons/acre) measured at gaging station.

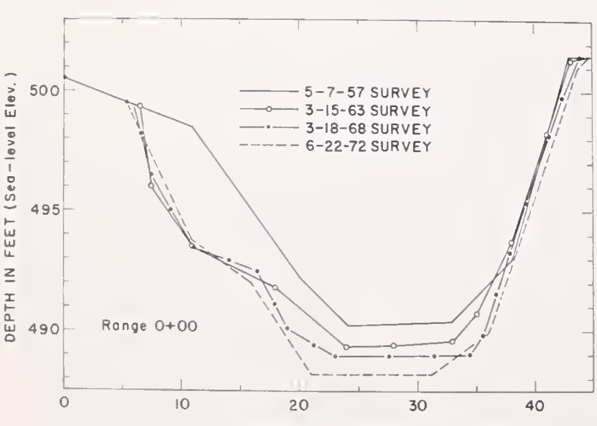

FIGURE 6.—Channel 4 cross section.

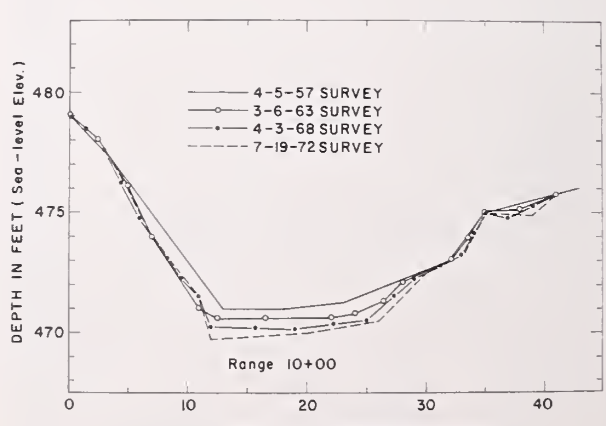

FIGURE 7.—Channel 5 cross section.

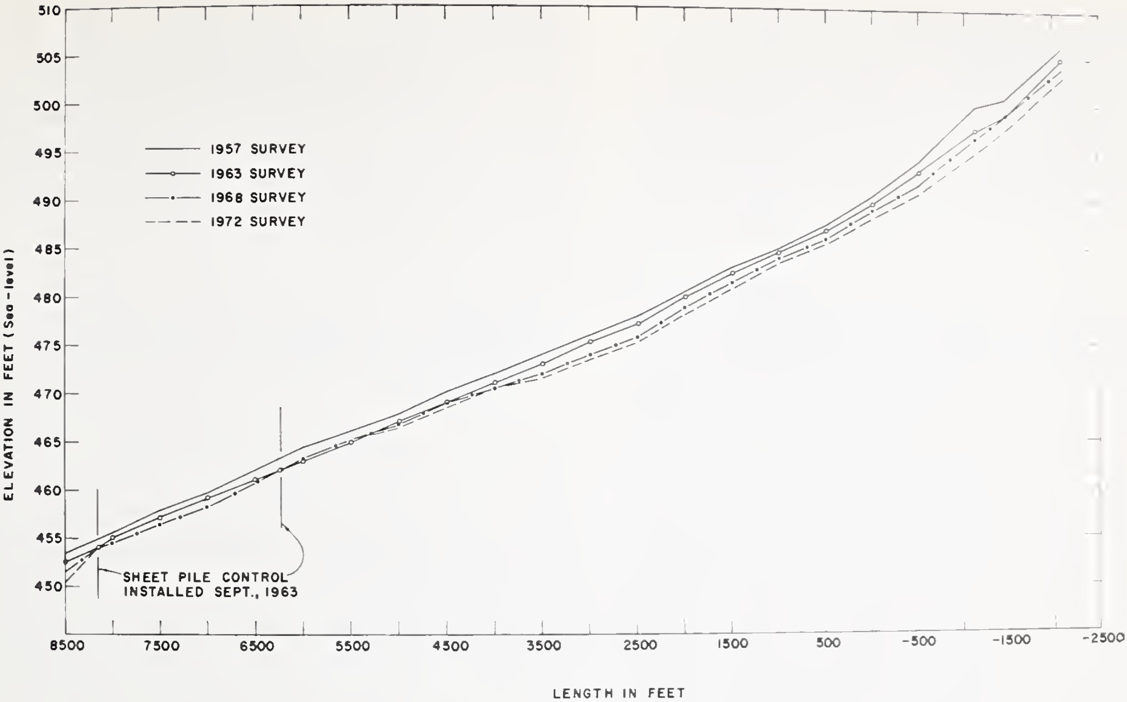

FIGURE 8.—Channel 4 profile.

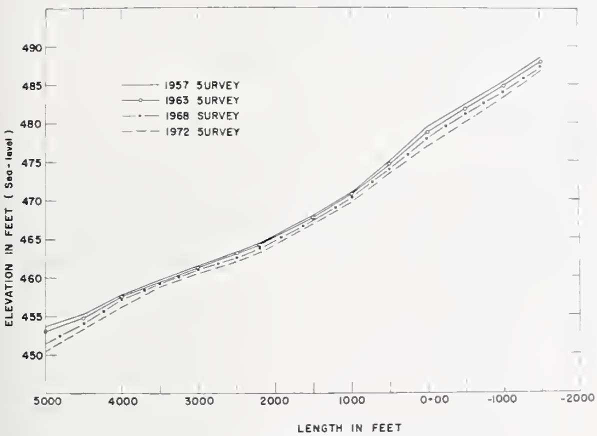

FIGURE 9.—Channel 5 profile.

tionally the capacity of the flowing water to transport materials previously deposited in the channel.

Another factor that may be significant is channel transmission losses. The ground-water table in watershed 4 is several feet below the channel beds in most places. In watershed 5 the ground water intersects the streambed of the main channel and major tributaries at several points. Consequently, the channel bed remains wet even during periods of prolonged drought. Generally, the bank material in watershed 5 is composed of less permeable material than that of watershed 4. Grissinger (*5, 6*) concluded that the susceptibility of most impermeable material to erosion was less on continuously wet soil than on soil alternately wet and dry. In general, the measured erosion rates decreased with increasing aging or wetting time.

Under most conditions, only a portion of the eroded material constituting gross erosion completely leaves a watershed. The percentage of sediment delivered from the upland point of detachment to a specified location downstream in a watershed is influenced by such factors as size and complexity of the drainage network, size and texture of erodible material, land use, and general physiographic position. Eroded materials are deposited in grass waterways, along field boundaries, in terrace channels, along flood plains, and at the toe of field slopes within the watershed (*14*). Consequently, gross erosion must be adjusted downward in order to estimate sediment yield at a particular point. This downward adjustment is expressed as the delivery ratio and in common usage is the percentage of computed gross erosion reaching the measuring point. The greater the sediment-delivery ratio, the greater the sediment yield; and as sediment yield increases, less of the detached or eroded material is trapped within the watershed (*11*).

If true values are to be assigned to the ratio of sediment delivered by overland flow to a specified point in a stream channel, it is necessary to consider the amount that the channel contributes to total sediment yield. Computed gross erosion and adjusted sediment-delivery ratios are shown in table 4. The delivery ratios were adjusted in an amount proportional to the average annual yield attributed to channel erosion. As would be expected, the adjusted delivery ratios were much higher for watershed 5 than for watershed 4. The average adjusted delivery ratio for the period of record was 39 pct for watershed 5 and 18 pct for watershed 4.

CONCLUSIONS

Although the weighted precipitation on the watersheds for a 14-yr period was nearly equal, analysis of the runoff data show that runoff and sediment yields were consistently related by a ratio of 2 to 1. Geological and soil factors were the major contributors to the difference in runoff between the two watersheds.

Land use did change considerably during the reporting period. There was an overall reduction of 8 pct in total cultivated area in watershed 4, as compared to a 5-pct increase in watershed 5. Pasture and forestland, classified as good-to-excellent cover, increased 35 pct in watershed 4 but only 3 pct in watershed 5. Changes in land use were reflected in the computations of gross erosion. Computed gross erosion from watershed 4 was reduced by 12.2 tons/acre during 1957–72. In watershed 5 gross erosion was reduced by only 1.4 tons during the same period of time.

The sediment yield per inch of runoff was essentially the same for both watersheds over the period of record. Channel erosion accounted for 40 pct of the average annual sediment yield in watershed 4 and 16 pct in watershed 5. In order to determine the sediment-delivery ratios of computed sheet and gully erosion, measured sediment yields were reduced by the amount of channel erosion which occurred during the period of record. The 2-to-1 runoff ratio for these two adjacent watersheds, which otherwise are similar in many respects, is a good example of why it is so difficult to develop runoff prediction models for ungaged watersheds.

ACKNOWLEDGMENTS

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TOTAL SEDIMENT LOAD BY THE EXTRAPOLATED DATA PROCEDURE[1]

By Paul B. Allen and Bill B. Barnes[2]

INTRODUCTION

Accurate sediment-transport data are often needed in hydrologic research and in the engineering design of water-control structures. For data-collection programs where samples of suspended sediment are taken with depth-integrating samplers, a portion of the flow depth cannot be sampled because the sampler nozzle does not travel all the way to the bed. This unmeasured distance varies from 0.30 to 0.49 ft, depending upon the sampler. According to Colby and Hubbell (*5*),[3] unmeasured transport can amount to over 60 pct of total transport. Sampling of the total load is possible if sampling is done at severely contracted stream sections where there is great turbulence or at manmade overfalls designed so that the sampler nozzle can pass completely through the flow. Channel contractions, however, are rarely near gaging stations, and costs of overfall structures usually prohibit their use. Therefore, computational procedures are usually used to determine total transport. There are only two computational procedures developed specifically to compute the total transport when measured load is determined with depth-integrated samples. These are the modified Einstein procedure (Colby and Hembree, *4*, and Colby and Hubbell, *5*) and a method based on mean velocity introduced by Colby (*3*).

Values of total transport can be determined by such procedures or equations as the Einstein, Meyer-Peter and Mueller, or Schoklitsch to predict the bed-material transport and by using the finer sediment fractions of depth-integrated samples to determine the wash load. Where accurate total transport data are desired, however, such predictions are impractical because inherent prediction errors of bed-material equations are so large that total transport by this procedure will often be less than the transport determined from depth-integrated samples alone.

Numerous comparisons of unmeasured load computed by the modified Einstein and Colby procedures were made for four Washita River gaging stations and two tributary stations. The agreement between the procedures was only fair, and it could not be determined which procedure was more accurate. Attempts were made to evaluate the accuracy of the two methods by Brooks' (*2*) modification of the Einstein procedure. Because this procedure uses field-determined velocities and sediment concentrations to calculate total suspended transport, it conceivably should have provided an accurate basis for comparison. Total suspended loads computed by this method, however, were sometimes less than measured loads, a physical impossibility. As reported by Allen and Welch (*1*), better results were obtained by determining a ratio of the transport computed for the total depth to that computed for the measured depth, both transports being computed by the Brooks' modification. The load computed from depth-integrated samples was multiplied by the above ratio to get the total suspended load. The fact that field-obtained velocities did not agree with the logarithmic velocity equation used in the Brooks' modification probably caused computed total loads to be less than measured loads. The Brooks' modification was also objectionable because of

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[3] Italic numbers in parentheses refer to items in "Literature Cited" preceding the appendix to this paper.

the large amount of field data required, necessitating considerable laboratory and office time. To circumvent both problems, a new method, called the extrapolated data procedure, was developed.

This paper details the development of the extrapolated data procedure and shows comparisons of unmeasured loads determined with computations by the modified Einstein, Colby, and extrapolated data procedures. The step-by-step computational procedure is given in the appendix to the paper.

DEVELOPMENT OF THE NEW PROCEDURE

The same general transport equation used by Einstein (*6*) and Brooks (*2*) was used:

$$q_s = \int c \cdot v \cdot dy, \tag{1}$$

where q_s = sediment transport per unit of width,
c = sediment concentration,
v = velocity,
and y = distance from the bed.

The classical sediment-distribution equation introduced by Rouse (*8*) was selected for use in the extrapolated data procedure. This equation is

$$\frac{c}{c_a} = \left(\frac{d-y}{y} \cdot \frac{a}{d-a} \right)^z , \tag{2}$$

where c and c_a = concentrations of suspended sediment at distances y and a above the bed, respectively,
d = stream depth,
$z = \frac{v_s}{ku*}$
v_s = fall velocity of the sediment particle,
k = von Karman constant,
$u* = \sqrt{gdS}$ = shear velocity,
S = energy gradient,
and g = gravity acceleration constant.

The z values were determined from the field data. If the concentrations, c, are plotted against the associated $\frac{d-y}{y}$, both on logarithmic scale, z is the slope of the line through the data with respect to the $\frac{d-y}{y}$ scale. The collected data, in general, made good straight-line plots. If the point where $\frac{a}{d-a} = 1.0$ is chosen, and the associated c_a is called c_0, equation 2 becomes

$$c = c_0 \left(\frac{d-y}{y} \right)^z , \tag{3}$$

which is the form used in the extrapolated data procedure. Other relations of sediment distribution, such as those by Willis (*10*) and Toffaleti (*9*), were not considered because of good data fits with equation 3. The other methods were also more complex and therefore more difficult to apply. It is recognized, however, that the relation used by Toffaleti greatly simplifies integration of the general transport equation, equation 1.

For velocity distribution in the vertical direction, the widely used logarithmic velocity equation was first investigated:

$$v = v_{\max} + \frac{2.30u*}{k} \log_{10} \frac{y}{d}, \tag{4}$$

where v = velocity at any distance, $\frac{y}{d}$, above the bed,
and $v_{\max}$ = the maximum velocity, usually assumed to be the surface velocity where $\frac{y}{d} = 1.0$.

Figure 1 shows plotted data from the Washita River gaging station at Verden, Okla. The distance from the bed, $\frac{y}{d}$, is plotted on a logarithmic scale against the associated velocity on a linear scale. Although the data make good straight-line plots around mid-depth, the velocities near the surface are much too low. This probably is caused by secondary currents in the flow. These low velocities near the surface might also explain, as mentioned earlier, why total transports computed by the Brooks' modification were sometimes less than measured transports.

Another problem with the logarithmic velocity equation was that the velocity commonly reached zero at some distance above the bed. For instance, in figure 1, velocities in verticals 27, 33, and 51 reached zero at 0.05, 1.1, and 0.01 ft above the bed, respectively. To eliminate the latter problem, a power function velocity equation was selected. Although data fits over the entire depth

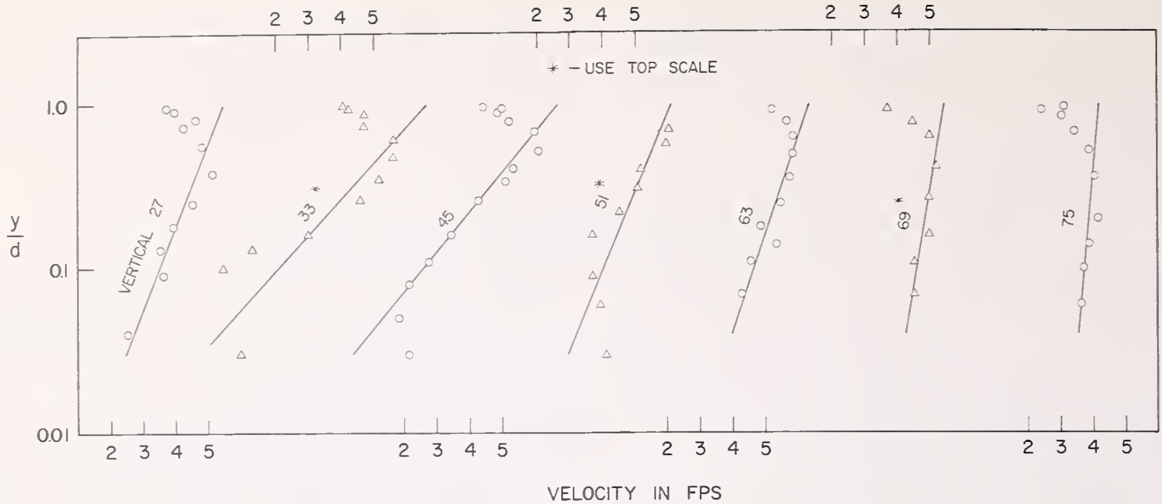

FIGURE 1.—Vertical velocity distributions for a 4,360-ft³/s flow, Washita River near Verden, Okla.

were not as good as the logarithmic relation, data fits below mid-depth appeared to be just as good. Extrapolating velocities toward the bed appeared more logical because no negative velocities could result. To determine the power function equation, plot the velocities, v, against associated distance from the bed, y, both on logarithmic scale. The equation is of the form

$$v = v_0 y^m, \tag{5}$$

where v = velocity at any distance, y, from the bed,

v_0 = velocity at $y = 1.0$,

and m = slope of a line through the data with respect to the distance, y, scale.

A velocity equation developed by Willis (*11*) was also investigated. This relation was developed by applying an error function approximation to the turbulent momentum diffusion coefficient. When field data below mid-depth were fitted to this equation, the bulk of the predicted velocities in the unmeasured zone either closely followed the power function predictions or fell about midway between the power function equation and the logarithmic velocity equation predictions. The maximum difference in transport in the unmeasured zone for the three methods was 30 pct of the average of all three transports. When differences were compared on a total sand transport basis, however, the maximum difference was only 4 pct. Further research is still needed on the best velocity equation for natural streams.

When concentration equation 3 and velocity equation 5 are substituted in general transport equation 1 and limits of integration and a unit conversion constant are added, the following equation, with terms as previously defined, is obtained:

$$q_s = 0.0027 c_0 v_0 \int_{y=2D\text{ ft}}^{y=0.3\text{ ft}} y^m \left(\frac{d-y}{y}\right)^z dy. \tag{6}$$

The lower limit of integration was chosen as $2D$, or twice the mean grain size of the bed material, as suggested by Einstein (*6*). For the Washita River bed material, $2D$ is approximately 0.001 ft. The upper limit of integration was chosen as 0.3 ft because nearly all the depth-integrated samples were taken with a U.S. D-49 sampler. Although the vertical distance from the nozzle to the sampler bottom is 0.33 ft, it was assumed that the sampler sinks into the bed sand a few hundredths of a foot, resulting in the 0.3-ft distance. The constant, 0.0027, converts q_s to tons per day when v_0 is expressed in feet per second and d and y are expressed in feet.

Although equation 6 can be integrated when z and m are integers, there is no general solution. Rather than use one of the approximation procedures, such as the Gaussian quadrature procedure, to solve the integral, the authors chose arithmetic integration with an electronic computer. When Δy increments of 1.25×10^{-4} ft were used, maximum errors from computer integration were less than 0.2 pct for the Washita River data. Although computer integration is generally preferable, a solution nomograph, shown in figure 2, was prepared to provide a quick estimate

of q_s when the variables z, d, m, c_0, and v_0 are known. The nomograph was constructed with a bed-sedment mean size of 5.0×10^{-4} ft. If the nomograph is used for sediment sizes slightly larger or smaller, no appreciable prediction errors result. The nomograph should not be used, however, for bed sediments with mean sizes more than twice this size, because with relatively high z values, errors of 20 pct or more are produced.

Unmeasured sand-transport determinations must be made for each sand-size range at each vertical because the particle fall velocity varies with the particle size, resulting in different c_0 and z values in the concentration distribution equation. The c_0 and z values usually vary for the same sediment-size range from vertical to vertical because of different turbulence and secondary current conditions. Sand-size ranges that are satisfactory for these calculations are those recommended by the Subcommittee on Sediment Terminology of the Committee on Dynamics of Streams of the American Geophysical Union

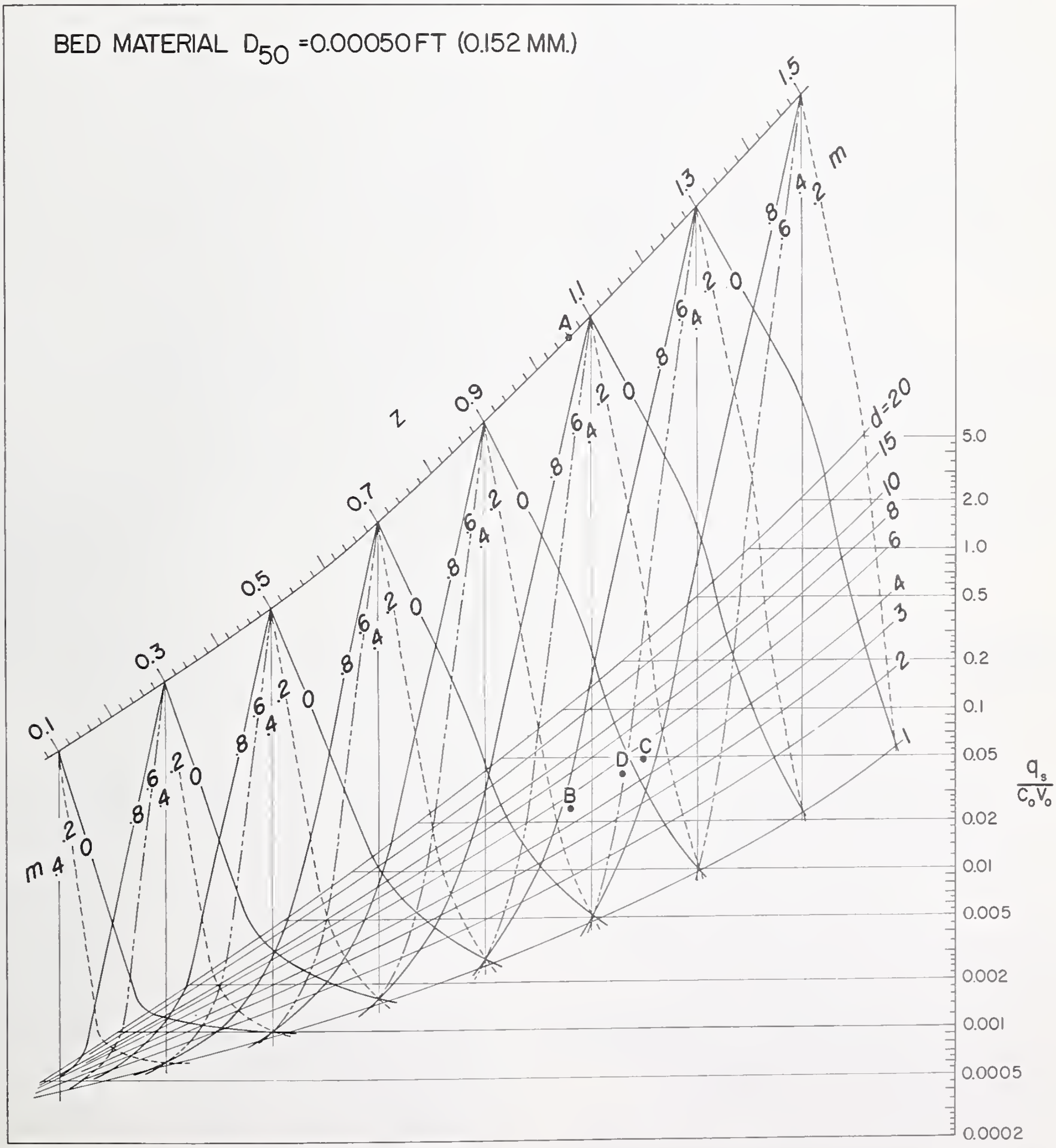

FIGURE 2.—Nomograph to determine sediment load in the unmeasured zone by the extrapolated data procedure.

(*7*). Size ranges for very fine sand, fine sand, and medium sand are 0.062 to 0.125, 0.125 to 0.250, and 0.250 to 0.500 mm, respectively.

Each sand transport, q_s, represents transport per foot of width. The width, w, associated with each vertical is assumed to reach halfway to adjacent verticals. Each q_s is multiplied by the associated width to determine Q_s, the transport per width increment. All Q_s values are totaled to determine total sand transport in the unmeasured zone.

Next, sand transport in the measured zone must be determined. The concentration of sand should already be known from depth-integrated samples that were taken down to $y=0.3$ ft. An adjustment must be made in the discharge, however, because it represents flow for the entire depth. For each vertical, v_0 and m values of the velocity distribution equation are already known. The discharge, q, per foot of width in the unmeasured zone is represented by the integral

$$q=\int_{y=0.001\text{ ft}}^{y=0.3\text{ ft}} v\cdot dy. \qquad (7)$$

If velocity equation 5 is substituted in equation 7, the integral becomes

$$q=v_0\int_{y=0.001\text{ ft}}^{y=0.3\text{ ft}} y^m\cdot dy. \qquad (8)$$

Integration of equation 8 gives

$$q=\frac{v_0}{m+1}(0.3^{m+1}-0.0001^{m+1}). \qquad (9)$$

The discharge, Q, associated with each vertical is obtained by multiplying the computed discharge per foot of width, q, times the width, w, associated with each vertical. All Q's are summed to obtain the discharge in the unmeasured zone for the entire stream cross section. This latter discharge must be subtracted from the total discharge of the stream to determine the discharge in the measured zone. The measured zone sand transport is the product of the measured zone discharge, the concentration of sand in the depth-integrated samples, and the constant 0.0027.

The final component of total transport is the fine material load or all material finer than sand-size material. It has been found from experience that the silt and clay particles are so uniformly mixed in the Washita River that separate calculations of the measured zone and unmeasured zone are unnecessary. Therefore, the total transport of fine material is found by taking the product of the total discharge, the concentration of silt and clay in the depth-integrated samples, and the constant 0.0027. Total transport is finally the sum of measured sand transport, unmeasured sand transport, and fine material transport.

It should be pointed out that the foregoing procedure does not account for bedload, or contact load, as it is sometimes called. From numerous modified Einstein calculations it was determined that bedload on the Washita River was such a small percentage of the yearly transport that it generally could be ignored. If bedload amounts are needed, they can be calculated with the Einstein bedload function procedure (*6*) or the modified Einstein total load procedure (*4, 5*).

COMPARISON OF COMPUTED TRANSPORTS

The necessary field data were collected so that total loads could be computed by the extrapolated data, modified Einstein, and Colby procedures. Data were collected from six discharge rates at four gaging stations on the Washita River in Oklahoma. Data at each discharge rate included a discharge measurement, depth-integrated sediment samples, bed-material samples, and the flow temperature. In addition, velocity measurements were made and point-integrated suspended-sediment samples were taken in 2 to 5 points below mid-depth in 7 to 10 verticals.

Table 1 compares unmeasured loads determined with the extrapolated data, modified Einstein, and Colby procedures. It should be pointed out that there is several times more transport in the unmeasured zone than these figures indicate. This results from the somewhat ambiguous method of computing measured transport. Measured transport is determined with mean concentrations from samples taken down to 0.3 ft from the bed multiplied by the flow that goes all the way to the bed. This so-called measured transport therefore represents transport in both the measured and unmeasured zones. It is missing only bedload and the difference in transport caused by using a measured mean concentration instead of the total mean concentration. The unmeasured data given in table 1 represent this difference.

TABLE 1.—*Comparison of unmeasured load computed by three procedures*

Washita River (Okla.) gaging station	Drainage area[1] (mi²)	Date	Discharge (ft³/s)	Measured transport (tons/d)	Bedload[2] (tons/d)	Unmeasured transport[3] (tons/d)		
						Extrapolated data	Modified Einstein	Colby
Anadarko	2,160	05–13–64	1,630	24,300	(4)	320 (1.3)	(4)	2,470 (10.0)
Do	2,160	11–06–64	3,860	55,200	(4)	330 (.6)	(4)	4,260 (7.7)
Verden	2,587	11–07–64	4,360	57,600	200	590 (1.0)	1,990 (3.4)	3,450 (5.9)
Chickasha	2,763	06–26–63	2,390	69,000	100	240 (.3)	780 (1.1)	1,580 (2.3)
Alex	3,290	06–27–63	1,250	29,700	120	670 (2.2)	1,690 (5.6)	2,510 (8.3)
Do	3,290	11–09–64	4,250	85,900	250	4,730 (5.2)	3,270 (3.6)	7,690 (8.5)

[1] Excludes the area above Foss Reservoir. [2] Computed by modified Einstein procedure.
[3] Numbers in parentheses are values of unmeasured loads as percentages of total loads.
[4] No computation for lack of bed material on unbroken sandstone bed.

The bedload data given in table 1 were determined with the modified Einstein procedure. These data have been added to the extrapolated data procedure values for a more valid comparison because the modified Einstein and the Colby unmeasured load data already contain bedload. As table 1 shows and as previously stated, little is lost if bedload is ignored for this particular river.

For the two flows at the Anadarko station that have an unbroken sandstone bed, very little is gained by making a total load computation. The extrapolated data procedure figures show that only 1.3 and 0.6 pct of the total transport is unmeasured load. Modified Einstein calculations could not be made at this station for the lack of bed material. Computations by the Colby method at this station were about 10 times too high. The Colby procedure is supposed to be used only for sand-bed streams.

The river channel at the Verden station and the Chickasha station is relatively narrow and deep. The extrapolated data procedure figures show that only 1.0 and 0.3 pct of the total transports were unmeasured. Modified Einstein computations are slightly high but not objectionably high. Colby computations are roughly 6 times too high.

The channel at the Alex station is wider and shallower than the others. Here the extrapolated data computations show that 2.2 and 5.2 pct of the total load is unmeasured load. The modified Einstein computation predicts twice too much for the smaller flow, but underpredicts the larger flow rate. Computations by the Colby procedure overpredicted both flows.

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APPENDIX.—STEP-BY-STEP CALCULATION OF TOTAL LOAD BY THE EXTRAPOLATED DATA PROCEDURE

1. For each sand fraction in each vertical, plot concentration against corresponding $\frac{d-y}{y}$, both on logarithmic scale, as shown in figure 3, and fit a straight line. Pick the intercept, c_0, where the line crosses 1.0 on the $\frac{d-y}{y}$ scale. Pick a second concentration, c_1, where $\frac{d-y}{y}$ equals 10.0. Compute the slope, z, of the line by the equation

$$z=\log_{10}\frac{c_1}{c_0}.$$

Record all c_0 and z values as shown in figure 4.

2. For each vertical, plot velocities against corresponding distances from the bed, y, both on logarithmic scale, as shown in figure 5, and fit a straight line. Pick the intercept, v_0, where the

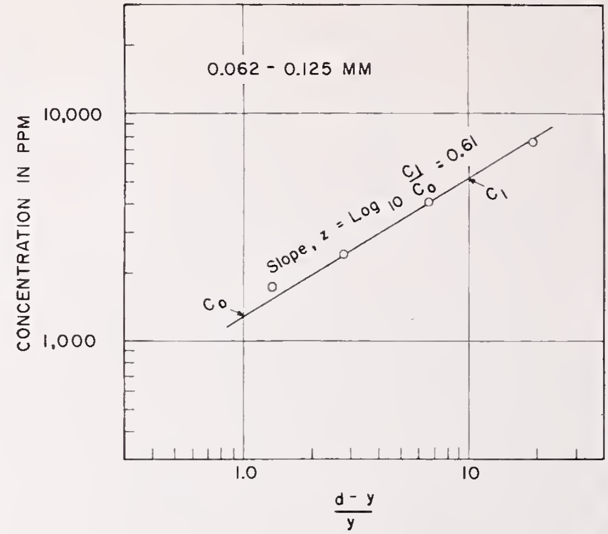

FIGURE 3.—Typical plotting of concentration data to determine slope, z, and intercept, c_0.

Station: Washita River at Alex, Oklahoma Date: 11-9-64 Time: 1016-1314
Mean gage height: 12.03 feet Flow: 4,250 cubic feet per second
Measured concentration: Fines (<0.062 millimeters) 5,480 parts per million
Sand (>0.062 millimeters) 2,010 parts per million

Vertical (ft)	Sand fraction (mm)	z	Depth d (ft)	m	$\frac{q_s}{c_o v_o}$	v_o (fps)	c_o (ppm)	Unmeasured transport q_s (tons/day/ft)	Width w (ft)	Unmeasured transport Q_s (tons/day)	Flow adjustment q (cfs/ft)	Flow adjustment Q (cfs)
140	0.062-0.125	.30	7.2	.78	0.00055	1.85	1,770	1.8	10	18	.22	2.2
	0.125-0.250	.67	"	"	0.00233	"	330	1.4		14		
150	" "	.74	6.8	.22	0.0121	4.95	1,850	111	"	1,110	1.15	11.5
		1.05	"	"	0.059	"	205	60		600		
160	" "	.61	6.1	.28	0.0052	4.78	1,280	32	"	320	1.07	10.7
		.92	"	"	0.0221	"	102	11	"	110		
170	" "	.73	7.2	.17	0.0139	5.35	1,180	88	"	880	1.31	13.1
		.91	"	"	0.035	"	180	34		340		
180	" "	.53	7.8	.34	0.0037	4.02	1,100	16	"	160	.87	8.7
		1.12	"	"	0.066	"	115	31		310		
190	" "	.48	7.8	.23	0.0038	4.69	1,200	21	"	210	1.06	10.6
		.94	"	"	0.036	"	140	24		240		
200	" "	.24	7.9	.14	0.00164	4.75	1,060	8.3	"	83	1.20	12.0
		.62	"	"	0.0094	"	260	12		120		
210	" "	.22	8.5	.18	0.00140	4.39	960	5.9	"	59	1.05	10.5
		.70	"	"	0.0131	"	223	13		130		
220	" "	.15	9.1	.26	0.00088	3.66	900	2.9	"	29	.81	8.1
		.46	"	"	0.0035	"	250	3.2		32		

Unmeasured sand transport = 4,765 Flow adjustment 87.4

Measured sand transport =
(total flow − flow adjustment) x measured sand in parts per million x .0027 =
(4,250 − 87) x 2,010 x .0027 = 22,593 tons per day

Measured fines transport (<0.062 millimeters) =
total flow x measured fines in parts per million x .0027 =
4,250 x 5,480 x .0027 = 62,883 tons per day

Unmeasured sand transport = 4,765 tons per day

Total transport = 90,241 tons per day

FIGURE 4.—Computational form for unmeasured sediment transport, flow adjustment, and total sediment transport.

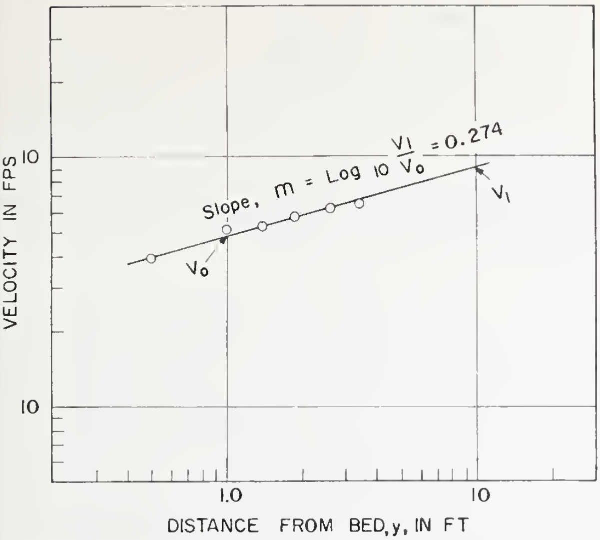

FIGURE 5.—Typical plotting of velocity data to determine slope, m, and intercept, v_0.

line crosses 1.0 on the distance scale. Pick a second velocity, v_1, where the distance, y, equals 10.0. Compute the slope, m, of the line by the equation

$$m = \log_{10} \frac{v_1}{v_0}.$$

This must be done for each vertical. Record all v_0 and m values on the form (fig. 4), duplicating these values for all sand fractions within a particular vertical.

3. Record depths, d, for each vertical on the form (fig. 4). Using the z, d, and m data on the form and the nomograph (fig. 2), compute and record $\frac{q_s}{c_0 v_0}$ for each sand size at each vertical. Use the nomograph as follows for an example where $z=1.06$, $d=5.0$, and $m=0.26$: Locate $z=1.06$ on the z scale, point A. Since $m=0.26$ is between $m=0.2$ and $m=0.4$, scale with dividers from point A to the nearest $m=0.4$ line. Transfer this distance downward, following the $m=0.4$ line and keeping the divider legs parallel to the initial setting and locate point B where the divider leg originally set on point A intersects the line where $d=5.0$. Next span from point A to the $m=0.2$ line. Transfer this distance similarly downward, following the $m=0.2$ line and establish point C. With the dividers, locate point D which is three-tenths of the C–B distance, to represent an m of 0.26. Horizontally from point D, read $\frac{q_s}{c_0 v_0}=0.039$.

4. Determine the transport, q_s, in tons per day per foot of width by multiplying $\frac{q_s}{c_0 v_0}$ by the associated c_0 and v_0 values from the form (fig. 4). As previously mentioned, numerical integration of equation 6 with an electronic computer may be preferable to steps 3 and 4.

5. The stream width, w, associated with each vertical is recorded on the form (fig. 4). The width of any particular vertical is usually assumed to reach half way to the adjacent verticals. Q_s in tons per day is computed for each sand size for each vertical by $Q_s = q_s w$ and recorded.

6. All Q_s values are totaled. This represents unmeasured suspended-sand transport below $y=0.3$ ft.

7. Measured and transport must now be computed. The concentration of sand should already be known from depth-integrated samples that were taken down to a y of 0.3 ft. An adjustment must be made in the discharge, however, because it represents flow for the entire section. With the nomograph (fig. 6) and the same vertical velocity m and v_0 values on the form (fig. 4), q's

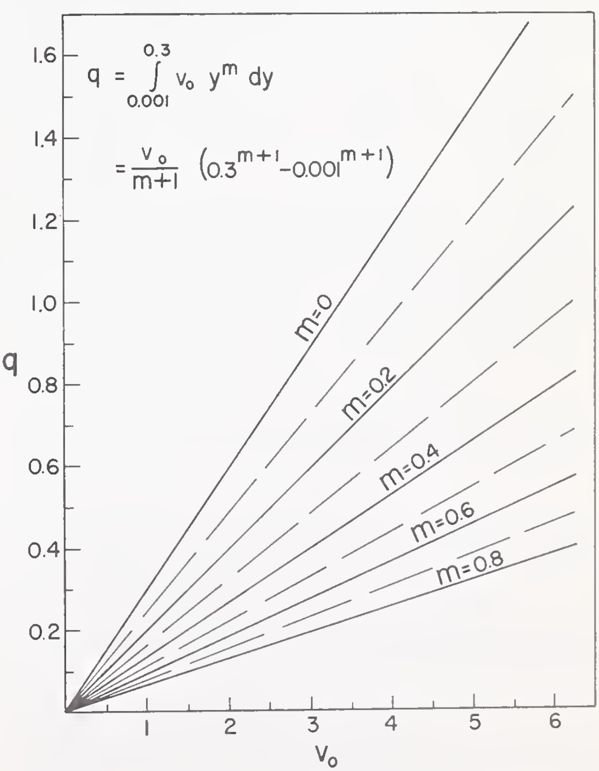

FIGURE 6.—Graph to determine discharge, q, in cubic feet per second per foot of width for the unsampled depth.

are determined for each vertical in cubic feet per second per foot of width for the bottom 0.3 ft of depth. These q's are multiplied by the applicable width, w, on the form (fig. 4) for each vertical to obtain Q's. These Q's are totaled and subtracted from the discharge for the total section. This measured zone discharge is multiplied by the sand concentration of the depth-integrated samples and 0.0027 to get the measured sand transport in tons per day.

8. The transport in tons per day of material finer than sand is computed by multiplying the total flow by the concentration of silt and clay in the depth-integrated sediment samples and by the constant, 0.0027.

9. Total transport is the sum of the unmeasured sand, measured sand, and fine-material transport.

ESTIMATING YIELD OF COARSE BED MATERIAL

By James L. Hunt[1]

In evaluating gross watershed erosion, one of the more elusive components of the erosion account is the quantitative value for sediments transported as bedload. The water conveyance systems with which the Soil Conservation Service (SCS) is concerned may operate infrequently as gullies or ephemeral streams or continuously as perennial streams. Evaluations of bedload movement may be made for one or more of the following purposes: determining, in part, the long-term sediment storage requirements for impoundment reservoirs; estimating the frequency of cleanout for debris basins; estimating changes in amounts of material movement through specific stream reaches as a result of storms or the installation of structural controls; ascertaining the likelihood of creating, by control, a self-armoring channel bed in specific reaches; and determining the stability of channel beds for specific flow conditions.

The use of computational procedures for bedload evaluations is often the only practical course available to SCS planning geologists; long-term case studies are not reasonably within the scope of their activities. Nor, in most cases, are long-term or even adequate short-term records of bedload measurements available for project areas of the sizes usually dealt with.

Although, in a few cases, measurements have been made of deposits in debris basins, on fans, and in channels of quantities moved in individual storms or a season's assortment of storms, there is no adequate substitute at present for field determinations, if they can possibly be made.

For field determinations various bed-material transport formulas are used as a basis for determining quantities of materials moved by stream discharges.

Most formulas were derived originally or were evaluated by the use of flume studies. Because the rigid side walls, uniform alinement, and steady or slowly changing discharge characteristics of flume studies are not reflective of natural conditions, doubt is cast on the limits of accuracy of a given formula's predictive capability when material sizes differ or are extended much beyond those of the test or experimental conditions. Doubt arises, too, when other parameters, such as discharge, slope, temperature, bed configuration, and material supply, also differ appreciably.

Unfortunately, most natural water conveyance systems do differ appreciably. As a result, the evaluations employing the transport formulas are probably more an indication of the magnitude of difference than an accurate measure of specific amounts.

The bed-material transport formulas most frequently used by SCS in their various program applications include several internationally familiar formulas: the Schoklitsch formula,[2] the Meyer-Peter formula,[2] the Haywood formula,[3] the Meyer-Peter, Muller formula,[2] the Einstein bedload function,[2] the Engelund-Hansen procedure,[2] and the Colby procedure for relating mean velocity to sand transport.[4]

In addition, in order to relate the movement of bed materials to field conditions, formulas or other expressions for determining the levels of

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[2] American Society of Civil Engineers, Committee on Sedimentation. 1969. Sedimentation manual. Sediment transportation mechanics—Sediment discharge formulas. Progress report on section H, chapter II, 53 pp.

[3] Haywood, O. G., Jr. 1940. Flume experiments on the transportation by water of sands and lightweight materials. D. Sc. thesis, Massachusetts Institute of Technology, Cambridge, 43 pp.

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entrainment are employed. These are variously referred to as tractive force, critical tractive stress, or critical velocity expressions.[5] Since all of the above formulas or expressions are well documented and well known to persons concerned with the field of sedimentation, they will not be reproduced here.

As indicated earlier, the use of formulas serves as a base upon which evaluations of bed-material movement are made. In conjunction with the use of formulas, various hydraulic and hydrologic evaluation procedures are needed to determine total quantities of materials moved by individual or selected discharge events.

SCS procedures usually begin with an evaluation of sources and availability of bed materials and with the collection of bed-material samples. Sampling procedures may vary depending upon the size and nature of material constituting the channel bed. Usually, a quantity of sample representative of a stream reach is collected, and the size distribution determined on the basis of weight. The effective diameter is determined in accordance with the requirements of the particular bedload formulas involved. The physical attributes of the channel reach are obtained from engineering data. A sediment-rating or sediment-discharge expression is developed that will provide, for a cross section or reach of stream channel, an indication of amounts of material moved by various rates of discharge. One such rating curve, for Mountain Creek near Greenville, S.C., is illustrated in figure 1.

The next step in the procedure requires an estimate of storms that will probably affect the channel reach (or the reservoir storage capacity) for the entire period over which a project is being evaluated. In the case of channel performance stability, aggradation and degradation evaluations would be based on a selected design event. For evaluating reservoir storage capacity it is frequently a 100-yr period. The evaluation for reservoir sediment-storage capacity is used as an example. In order to account for a total accumulation or movement of materials during the reservoir life, the discharges that can be expected to occur during that 100-yr period must be taken into consideration. Data are obtained in the forms of hydrographs representing a selected storm series; for example, those events having a 1, 2, 5, 10, 20, 50, and 100 pct chance of occurrence. Each hydrograph is divided into small

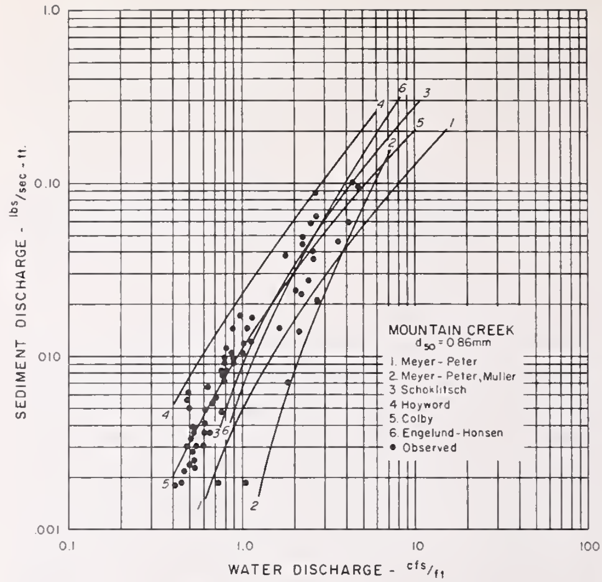

FIGURE 1.—Sediment rating curves for Mountain Creek near Greenville, S.C., according to several formulas compared with measurements. (Adapted from Vanoni, V. A., Brooks, N. H., and Kennedy, J. F. 1961. Lecture notes on sediment transportation and channel stability. California Institute of Technology Report No. KH-R-1, pp. 7–8.

time units so that amounts of bed-material movement for each unit may be conveniently determined.

Figure 2 illustrates a group of synthesized, triangular hydrographs of selected discharge events for a stream cross section for which no sediment-movement records are available. The triangular configuration facilitates longhand computation; the usual curvilinear shape is easily adaptable to computerized evaluations.

The point of initial material movement is determined either by using the tractive-force formula or by selecting a discharge from the sediment rating curve at which essentially no movement occurs. This "no movement" discharge is subtracted from the hydrograph in order that only that portion of the hydrograph for which sediment movement occurs is included in the accounting system. Then, for each of the hydrograph time units, the average sediment discharge is computed. The sum of these discharges for the time units constitutes an estimate of the total amount moved by the particular event. This procedure is repeated for each of the selected events. By constructing, on rectilinear graph paper, a plot of total bedload per event against per-

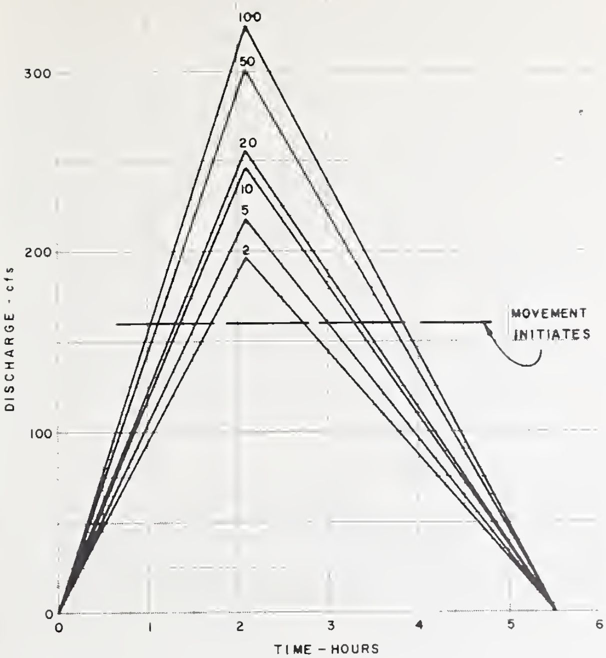

FIGURE 2.—Synthesized hydrographs of selected discharge events for a stream cross section.

cent chance of occurrence of events, it is simple to obtain a planimetered summation of total quantities moved for the complete range of events between 1 and 100 pct chance of occurrence. This, when divided by 100, is assumed to be equal to an average annual movement of material. An illustration of this is shown on figure 3. Figure 3 was developed to include only those events occurring between a 1 and a 50 pct chance.

On many occasions the evaluation of material movement is made for conditions in existence on the watershed, as compared to conditions that are projected to follow the installation of flood prevention projects. In this circumstance, a second evaluation is performed for those conditions that are proposed for the project. The difference between the amounts determined under each condition is considered to be part of the effect of the project and is associated with the changes in discharge resulting from project installation. In performing such evaluations several assumptions must be accepted: First, that the conditions

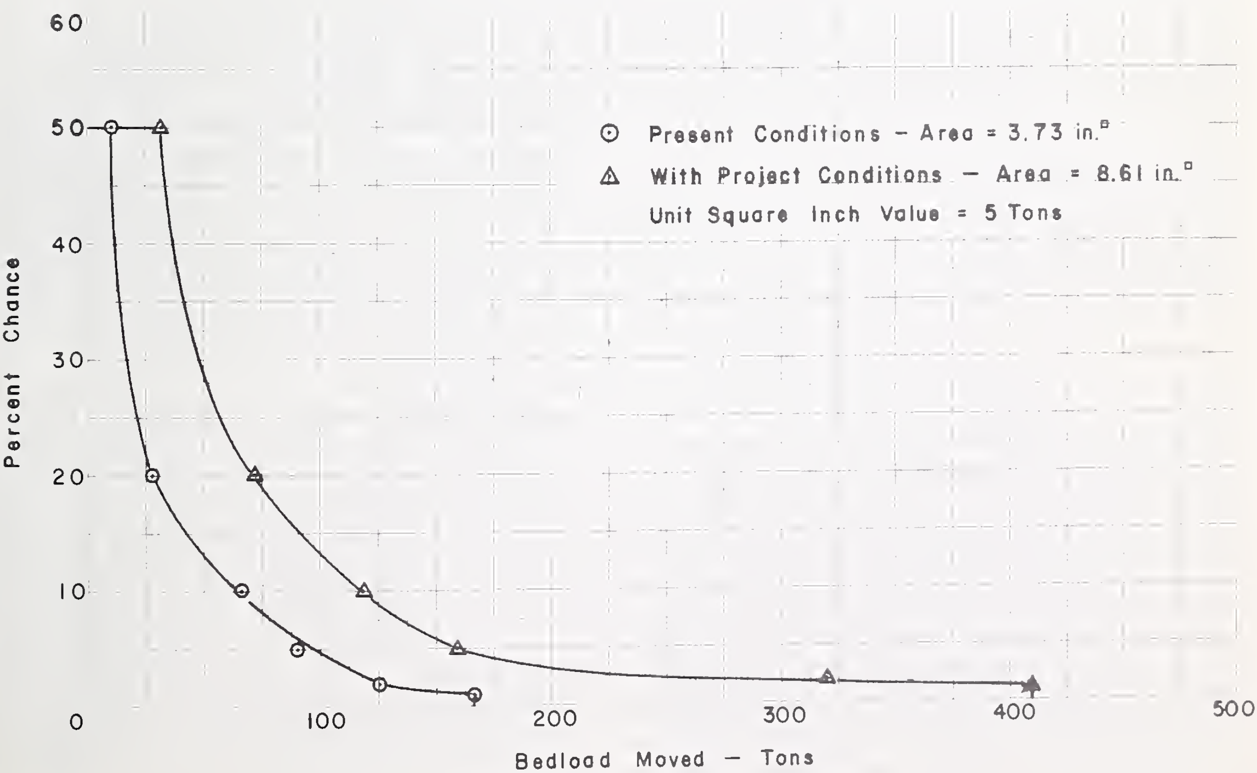

FIGURE 3.—Procedure to estimate bedload movement.

present in the field at the time the samples are obtained are representative of a wide scale of discharges; second, that the geometry of the reach will remain essentially unchanged over the project evaluation period; third, that the source of bed material will be neither depleted nor increased during the life of the channel; fourth, that the texture, gradation, and composition of the bed material will not materially change during the period; and, fifth, that the drainage characteristics of the contributing watershed will not be significantly altered. A most desirable addition to this kind of analysis would be to continue to analyze the same channels under "with project" conditions to obtain confirmation or corrective factors, and permit refinement and improvement of the elements of hydrology and sedimentation used in the procedures.

SOIL DETACHMENT BY RAINDROPS

By Calvin K. Mutchler[1] and Robert A. Young[2]

Raindrop impact is the primary source of energy for detaching soil from any land area not protected by cover of some sort. Raindrop impact also plays an important part in sediment transport by very thin waterflow. The direct role of raindrops in the mechanics of erosion is the subject of this paper.

RAINDROP CHARACTERISTICS

Raindrops range from about 7.0 mm in diameter to fine mist sizes. Most rainfalls are described by assuming a normal size distribution based on raindrop volumes. The median drop diameter, D_{50}, defined as the diameter where equal amounts of volume are contained in larger drops and in smaller drops, is used to describe rainfall. Median drop size is related to rainfall intensity as follows (*1*):[3]

$$D_{50}=2.23I^{0.182} \tag{1}$$

D_{50} ranges from 1.5 mm for an intensity of 0.1 inch/h to 2.5 mm for an intensity of 2 inches/h and larger for more intense storms. From the definition of median drop diameter, it is seen that very few raindrops larger than D_{50} are present in rainfall, while many raindrops are smaller than the median drop size.

Raindrops reach a terminal velocity that depends on their diameter. These velocities are, for instance, 3.3 ft/s for a drop 0.25 mm in diameter, 13.1 ft/s for a drop 1 mm in diameter, and 29.9 ft/s for a drop 5 mm in diameter. Actual impact velocity, however, is often greater than the terminal velocity because of wind effects which may impart an added velocity component. Wind will also cause raindrops to strike the soil surface at some angle with the vertical.

Using the drop size distributions of rainfall determined by Laws and Parsons and terminal velocities for the various drop sizes of rainfall, Wischmeier and Smith derived a single equation to describe storm energy for a given intensity (*8*).

$$Y=916+331 \log_{10} I \tag{2}$$

Here Y is the kinetic energy in foot-tons per acre-inch and I is the rainfall intensity in inches per hour. This equation, together with maximum 30-min storm intensity, form the basis of the EI variable which is an integral part of the universal soil loss equation.

RAINDROP SPLASH SHAPE

Some interesting deductions may be made by studying the splash shape dimensions and water movement resulting from raindrop impact. A high-speed picture study of splash (*2*) showed that splash-shape geometry could be described by the parameters shown outlined on the vertical cross section of a splash in figure 1. The parameters pictured are generally self-explanatory. The sheet angle α and the sheet radius r, which describe the profile of the cylindrical shell of flowing water, have not been particularly useful. However, the angle β, which describes the direction that droplets travel away from the splash sheet, has been useful in computing energy dissipation under the impacting waterdrop; this will be discussed later.

The parameter H describes the splash sheet

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[3] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this paper.

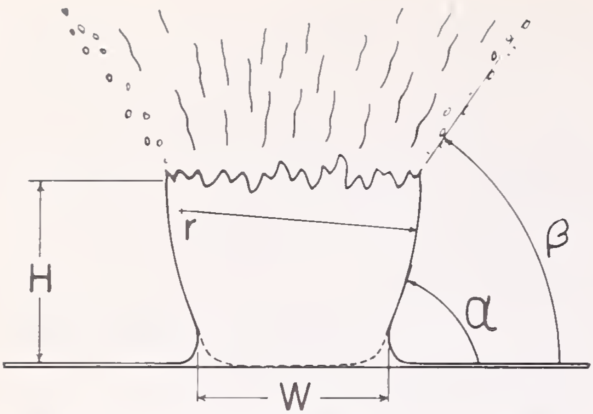

FIGURE 1.—Parameters for describing the geometry of splash shape.

height; its maximum, Hm, has been used to define a characteristic splash shape in order to determine the various effects of drop size and surface conditions on splash shape. The parameter W describes the crater width of the splash shape, and its change with time represents the horizontal flow velocity of surface water away from the impact site. Variation of the parameter values with time from drop impact are illustrated in figure 2.

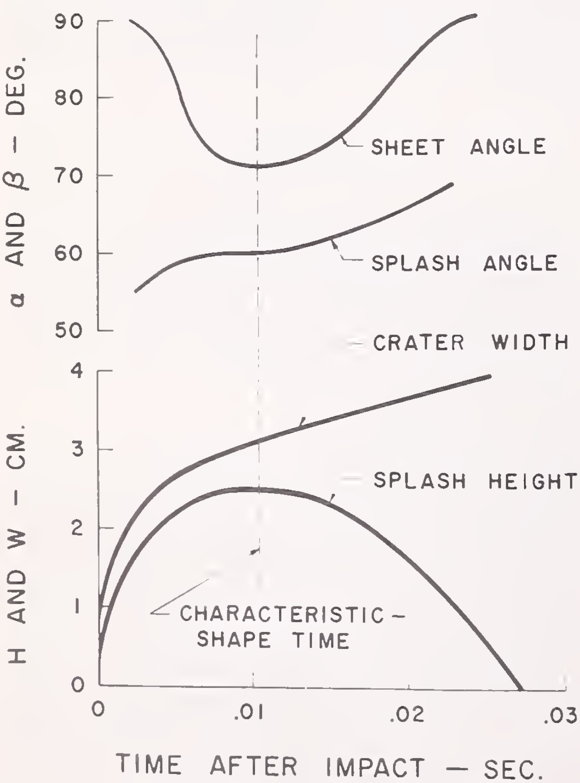

FIGURE 2.—Splash parameter change with time from impact. The characteristic shape time was selected at the time for maximum splash height.

The equation for the development of crater width under an impacting water drop is

$$\frac{W}{Wm}=\frac{1}{3.57}\log_e\left(\frac{T+0.03\,Tm}{0.03\,Tm}\right). \qquad (3)$$

Here, T is time since waterdrop impact and Tm is time for the splash shape to attain its maximum height. The equation was tested for $0.02\leq T/Tm\leq 2.0$ for the case of a drop falling on a smooth glass surface. Half the value of the derivative of equation 3 yields the horizontal velocity of water moving away from the impact site along the surface.

$$Vh=Wm/[7.14\,(T+0.03Tm)] \qquad (4)$$

The equations describing Wm and Tm as they vary with surface water depth, d, and waterdrop diameter, D, are given in Mutchler and Hansen (*6*). If the assumption can be made that shear velocity is related to soil detachment, equation 4 can be used to assess the erosiveness of raindrops falling on soil covered by thin layers of water.

For example, horizontal velocities of water under impact of a waterdrop 0.425 cm in diameter are given in figure 3 for time after impact and varying surface water depth. The straight lines showing critical velocity for detachment of underlying soil were computed with the viscosity equation

$$T=\mu\frac{dv}{dy}, \qquad (5)$$

where T=shear stress, μ=dynamic viscosity, v=particle velocity, and y=depth position. By assuming the observed velocity given by equation 4 equal to dv and $d/2$ equal to dy, a rough approximation for surface shear is

$$T=\mu\frac{Vh}{d/2}. \qquad (6)$$

An estimate of the minimum velocity required to detach soil particles from the surface was then computed with the critical shear force of the flowing surface water. Values for the range of critical force Tc were taken from Smerdon (*7*); these values are representative of cohesive agricultural soils.

Based on the above assumption, figure 3 illustrates two primary things about raindrop impact. First, the erosive action of a raindrop is

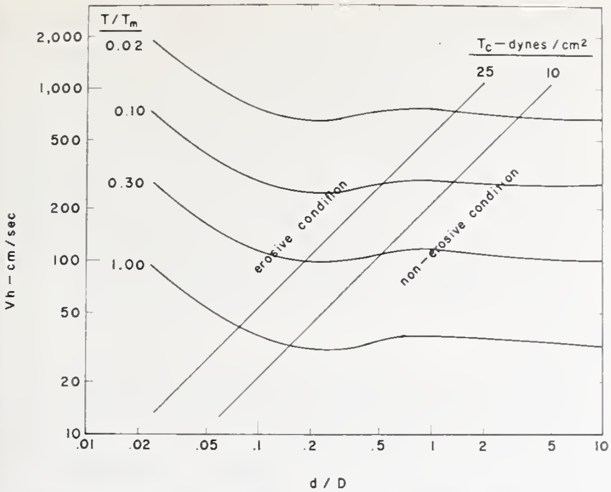

FIGURE 3.—Erosive surface flow velocities under an impacting waterdrop 0.425 cm in diameter.

effective very early after impact, and thus in the immediate vicinity of the center of impact. And second, support is given to the hypothesis that a surface water depth of about three drop diameters essentially protects soil from raindrop impact.

The horizontal velocities of flowing water under impacting raindrops also greatly increase the potential of thin surface flow to transport detached soil particles and aggregates. This will be discussed later in this paper.

The parameters *Hm* and *Wm,* which describe the size of the splash shape, vary according to water depth and waterdrop diameter. These parameters are largest (the splash is largest) for a depth of about one-third drop diameter. Also, very little change in the splash shape is seen at depths greater than three drop diameters. It can be inferred, then, that the impact of a raindrop 2 mm in diameter will have relatively little effect on soil covered by water 6 mm deep such as commonly seen in rills, tool marks, and mulch cover. Conversely, impact of this same drop on soil covered by water some two-thirds millimeter deep will have highly erosive effects.

SPLASH CHARACTERISTICS

Fundamental to the study of sediment transport by raindrop splash is the determination of the source and the amount of splash from a raindrop impact (*3*). Both splash magnitude and fraction of waterdrop in the splash vary with water depth and drop diameter (fig. 4). Total splash increases to a maximum of more than twice the waterdrop weight at a depth between 0.14 and 0.20 drop diameters (*4*). The influence of greater depth becomes relatively insignificant at a depth of about three drop diameters. Here, again, the evidence indicates raindrop impact is most erosive where a very thin layer of water is present (approximately one-fifth drop diameter here) and is relatively nonerosive when the soil is covered with a water depth of three drop diameters or greater.

Significantly, the major portion of splash originates from surface water. Thus, there is a potential to transport suspended soil by splash action alone. The particle sizes that can be transported by splash droplets, however, are limited by the small size of the droplets.

Large numbers of droplets are produced by waterdrop impact, especially on water depths less than 0.2 drop diameters; over 4,000 droplets were produced by the impact of one large drop, 5.6 mm in diameter, on a water depth of 0.1 mm overlying smooth glass (*5*).

The median diameters of the droplet distributions (on a volume basis similar to that of rainfall) were as large as 1.8 mm for impacting drops 5.6 mm in diameter in water depths of 0.5 mm. However, for a depth of one-fifth to one-third drop diameter, which has been indicated to be the most vulnerable case for soil detachment by raindrops, a raindrop 2.5 mm in diameter should produce droplets with a median diameter of about 1 mm.

Energy dissipation at the waterdrop impact site was estimated by calculating the difference between the waterdrop energy immediately be-

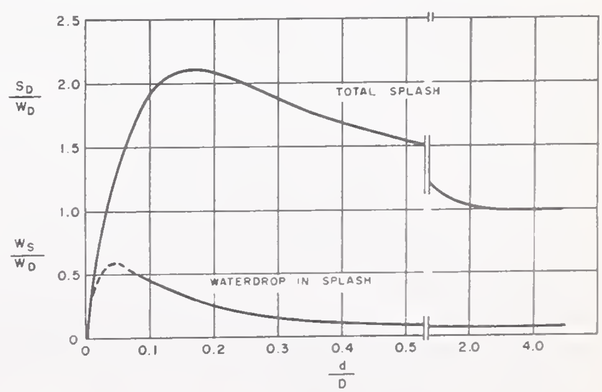

FIGURE 4.—Total splash S_D and waterdrop water in splash W_s expressed as a fraction of waterdrop weight for various water depths d expressed as a fraction of waterdrop diameter D.

fore impact and the energy of the splash droplets (*3*). At a depth of 0.1 drop diameter, approximately 90 pct of the waterdrop energy remained in the impact area; this was a minimum dissipation percentage. For all depths greater than 0.1 diameter, dissipation increased to 95 pct for deep water. The amount of energy transmitted through the water layer was not determined. However, deductions made earlier lead one to believe that much of the impact energy would be transmitted to soil surfaces underlying layers of water less than three drop diameters deep.

Raindrops are shown to have a great potential for detaching soil and a limited ability to transport soil directly. However, the horizontal velocities produced by drop impact very probably are the basis for transport of detached soil particles in thin layers of water flowing toward rills.

PLOT STUDIES

In a field study in which fluorescent glass particles and microrelief measurements were used to determine soil movement patterns on variously shaped slopes, the position of the particles after a simulated rainstorm and the fact that the particles moving off the plot did so primarily by transport in rills indicated that raindrop splash is a major contributor to soil detachment and to transport of soil particles to a rill system (*9*).

Experiments with simulated rainfall on an indoor plot of soil (*10*) further clarify the phenomena of soil detachment and transport. These experiments supported the conclusion that raindrop energy, rather than surface-flow energy, was the major force initiating soil detachment on interrill areas. Raindrop impact also contributed greatly to the transport of detached particles to a rill system. In this study, when rainfall energy was reduced by about 89 pct without decreasing intensity, the reduction in amount of soil moved to rills was 91, 95, and 90 pct, respectively, for a loam, silty loam, and a sandy loam soil. Thus, it was concluded that detachment and transport of soil from a nonrilled area is by raindrop impact action. However, soil carried by splash alone was only 10 to 17 pct of the loss from interill area to rills. The remainder of the loss to rills was carried in thin surface flow which, without raindrop impact, carried little, if any, soil. Therefore, it must be concluded that raindrop impact was the driving force to transport soil in thin surface flows to rills.

Over 80 pct of the soil moving off the 15-ft-long plot was transported in rills. Although this percentage would vary for various rill intensities and slope lengths, it is clear that most of the eroded soil is transported in a rill system.

SUMMARY AND CONCLUSIONS

In summary, the evidence indicates that raindrop splash is the primary agent in soil detachment and transport from interrill areas. On a saturated soil surface not protected by some cover of plant material or sufficient water depth, detachment results from the dissipation of impact energy. Soil is transported to rills partly by splash action alone, but the primary means of transport to rills is very thin surface flow accelerated by raindrop impact splash velocities.

Raindrop impact effects are probably present in rills themselves but they have not been studied in this research. The relative importance of rills and interrill areas as sediment sources depends, of course, on the number and size of rills in, for instance, a cultivated field.

Runoff and sediment follow the same path down a slope—from nonrill area to rill area to large watercourse. This helps explain why true sheet flow down a slope is rare. Soil loss in a rill system, then, is determined first by the supply of soil particles detached by raindrop impact, and next by transport of these particles in small channels—rill flow. At some point, the channel pattern may lead to very large rills (or gullies) which may be the main source of sediment from a watershed. Where banks of large watercourses or channel beds are the prime sources of sediment, it is doubtful that raindrop splash has significant effect, because of the limited areas involved.

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ESTIMATING THE SOIL LOSS EQUATION'S COVER AND MANAGEMENT FACTOR FOR UNDISTURBED AREAS[1]

By W. H. Wischmeier[2]

A numerical evaluation of the effectiveness of various types and qualities of cover and management as protection against the erosive forces of rainfall and runoff is a very important factor in sediment prediction. This factor has been evaluated for cropland from more than 10,000 plot-years of soil-loss data assembled from plot studies over the past 40 yr.[3] However, data are not now available for its direct evaluation for various wooded, range, and idle lands—areas that also contribute to watershed sediment loads. Use of either the Musgrave equation or universal soil loss equation to estimate the sediment contribution from such sources has required reliance on highly generalized judgment values for the cover and management factor.

This report presents a methodical routine and the necessary graphs for approximating the universal soil loss equation cover and management factor C for situations that are not represented in previous research data. The technique is based upon a refined interpretation of the empirically derived factor C.

INTERPRETATION OF COVER AND MANAGEMENT FACTOR

The effects of cover and management on soil detachment and transport by rainfall and runoff are numerous and varied. The erosion equation's empirically determined factor C combines all of these effects in one numerical evaluation. Extension of this factor to untested situations by objective analogy is facilitated by separating its total influence into three distinct types of effects and evaluating each type as a subfactor: type I—effects of canopy cover; type II—effects of mulch or close-growing vegetation in direct contact with the soil surface; and type III—tillage and residual effects of the land use.

Type I. Canopy Cover.—Leaves and branches that do not directly contact the soil are effective only as canopy cover. Canopies have little influence on the amount and velocity of runoff from prolonged rains, but they do intercept falling raindrops. Waterdrops falling from the canopy may regain appreciable velocity, but usually less than free-falling raindrops. Therefore, the canopy reduces rainfall erosivity by reducing its impact energy at the soil surface. The amount of reduction depends on the height and density of the canopy. This effect can be viewed as a reduction in the effective EI of rainstorms, and can be directly computed for specific situations.

The literature provides data on the velocities attained by waterdrops of various sizes falling from various heights.[4] Generally, the median drop diameter increases as rain intensity increases. For intensities of from 0.5 to 2.0 inches/h, the median drop size ranges from about 2.0 to 2.5 mm.[5] A 2.5-mm drop was assumed to be representative of erosion-producing rains and was used for analysis of the influence of changes in fall height on the effective EI. A 2.5-mm drop

[1] Cooperative research of the Agricultural Research Service, U.S. Department of Agriculture, and the Purdue Agricultural Experiment Station. Purdue Journal Paper No. 4916.

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[3] Wischmeier, W. H., and Smith, D. D. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains. U.S. Department of Agriculture, Agriculture Handbook No. 282, 47 pp.

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starting from zero velocity will reach a velocity of 3 m/s in a fall of 0.5 m, 4 m/s in a fall of 1 m, 5.2 m/s in a fall of 2 m, and 7.4 m/s in a fall of 20 m or more (table 1).

The kinetic energy of a given mass is directly proportional to the square of its velocity. For example, a 2.5-mm drop falling from a height of 2 m would have only half the kinetic energy of a free-falling raindrop of equal size ($5.2^2/7.4^2$). Since the interception by canopy does not appreciably affect the *I* component of the *EI* parameter, the reduction in effective *EI* is directly proportional to the reduction in impact energy.

For partial canopies, "percent cover" was defined as the percentage of the total surface area that could not be hit by vertically falling raindrops because of the canopy. Thus the effective *EI* for a given area is linearly proportional to the percentage of the ground that is not covered by the canopy.

Figure 1 was developed from terminal-velocity data used with the relationships cited above. If possible increase in drop size because of canopy interception is ignored, or is assumed to be offset by the fact that some of the intercepted water moves down the stems to the ground, the canopy factors for various percentages of cover at heights of 0.5, 1, 2, and 4 m may be obtained directly from this graph. For a 60-pct canopy cover at a height of 1 m, for example, the canopy factor is 0.58. This means that the effective *EI* with the canopy is only 58 pct of the actual *EI* of the rainfall, and the expected erosion would also be only 58 pct of that predicted by the *EI* obtained from the isoerodent map.

Figure 1 is based on a median drop size of 2.5 mm for both the rain and droplets formed on the canopy. In localities where rainfall is characteristically of low intensity, canopy effect would be less and the subfactor would be higher than shown by figure 1. If the 3.35-mm droplets measured by Chapman[6] on a red pine plantation are characteristic for pine tree canopies, figure 1 should be modified for that situation, also. For either of the two conditions, subfactor values for complete canopy cover can be computed from the data in table 1.

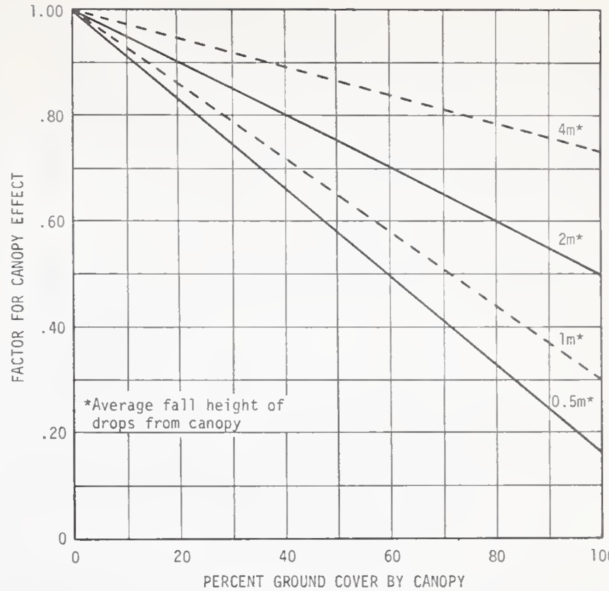

FIGURE 1.—Influence of vegetal canopy on effective *EI*, assuming bare soil beneath the canopy, and based on the velocities of free-falling waterdrops 2.5 mm in diameter.

Type II. Mulch and Close-Growing Vegetation.—A mulch on the soil surface is much more effective than an equivalent percentage of canopy cover. There are two reasons for this. Since the

[6] Chapman, Gordon. 1948. Size of raindrops and their striking force at the soil surface in a red pine plantation. Transactions of the American Geophysical Union 29: 664–670.

TABLE 1.—*Velocities, in meters per second, of falling waterdrops of different sizes after various heights of fall in still air*[1]

Rain intensity (inches/h)	Median drop diam. (mm)	Drop fall height (meters) 0.5	1.0	2.0	3.0	4.0	6.0	[2]20.0
0.5	2.00	2.89	3.83	4.92	5.55	5.91	6.30	6.58
1.0	2.25	2.93	3.91	5.07	5.74	6.14	6.63	7.02
2.0	2.50	2.96	3.98	5.19	5.89	6.34	6.92	7.41
4.0	3.00	3.00	4.09	5.37	6.14	6.68	7.37	8.06

[1] From Laws, J. O. 1941. Measurements of the fall-velocity of water-drops and raindrops. Transactions of the American Geophysical Union 22: 709–721.

[2] Values in the last column are considered terminal velocities.

intercepted raindrops have no remaining fall height to the ground, their impact on the soil surface is essentially eliminated. Probably more important, a mulch that makes a good contact with the ground also reduces the velocity of runoff. This, in turn, greatly reduces the runoff's potential to detach and transport soil material.

Substantial rainulator (rainfall simulator) data are now available on the erosion-reducing effectiveness of various amounts and types of mulch on cropland and construction sites. Extrapolation of these data to other mulches and close covers, such as those associated with range or woodland, is facilitated by expressing them on the basis of "percent surface cover" rather than tons of mulch per acre (fig. 2).

If the cover includes both canopy and surface mulch, the canopy and mulch factors overlap and cannot both be fully credited; the impact energy of a raindrop that strikes the mulch is dissipated at that point regardless of whether canopy interception has reduced its fall velocity. The mulch factor is taken at full value, and the canopy factor is reduced to apply only to the percentage of the surface not covered by mulch.

For illustration, assume a 30-pct mulch cover combined with a 60-pct canopy at a height of 1 m. From figure 2, the factor for mulch cover effect is 0.47. Because of the 30-pct mulch cover, the effective canopy cover is only 0.70 of the overall 60-pct cover, or 42 pct. Entering figure 1 with a 42-pct canopy cover, we obtain a factor of 0.70 for canopy effect. The factor for this combination of canopy and mulch cover is the product of the two subfactors 0.47 and 0.70, or 0.33.

Type III. Residual Effects of Land Use.—This category includes residual effects of the land use on soil structure, organic-matter content and soil density; effects of tillage or lack of tillage on surface roughness and porosity; roots and subsurface stems; biological effects; and probably other factors.

That the type III effect is often substantial is readily apparent from the soil-loss-ratio table in Agriculture Handbook 282. This is the table used to derive locational C-values for cropping systems. For plow-disk-plant systems, canopy cover and surface residue are negligible during the seeding period (crop stage 1) and the stubble period (crop stage 4R) for corn. Yet the soil-loss

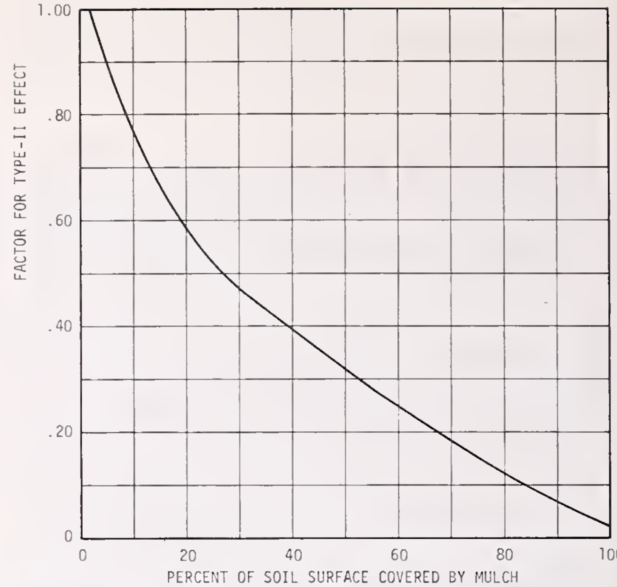

FIGURE 2.—Effect of plant residues or close-growing stems at the soil surface on C-factor (does not include subsurface root effects).

ratios for these crop stages range from 0.25 to 0.80. The amounts by which they are below 1.0 must represent primarily type III effects.

Values given in the handbook table for crop stage 1 are not quite the same as the corresponding values for stage 4R. Soil loss in period 4R is lowered slightly by a small amount of type II effect from the stubble and scattered residue remaining on the surface after silage harvest. When corn is grown in a sod-based rotation, the residual effect of the sod diminishes progressively through the first 2 yr after it is turned. This decline in residual effect more than compensates for the stubble effect and results in stage 4R values that are larger than the corresponding stage 1 values (see lines 1–7). It seems logical to assume that the average of the two values would reflect the type III effect during crop stage 3. The difference between this average value and the crop stage 3 value represents the effects of canopy and of increased transpiration by the plants. For example, line 1 of the handbook table gives values of 0.25, 0.17, 0.10, and 0.35 for crop stages 1, 2, 3, and 4R, respectively. The subfactor for type III effect during crop stage 3 is $(0.25+0.35)/2=0.30$, and the indicated canopy factor is $0.10/0.30=0.33$.

When the above procedure is used to obtain the subfactor for type III effect for the situation represented by a given line in the handbook table, and this is combined with the subfactors for type I and type II effects obtained from figures 1 and 2, the product of the three subfactors should very closely approximate the *C*-value shown in that line for crop stage 3. This was checked for corn and wheat.

Corn.—For corn in 40-inch row spacing, yielding more than 75 bu/acre, a 95-pct canopy cover during crop stage 3 was assumed. For yields of 65, 50, and 30 bu, assumed canopies were reduced to 87, 80, and 60 pct, respectively. Fall height of drops from blades of corn was assumed to average 1 m. From figure 1, the subfactors for type I effect of the various stands were 0.34, 0.39, 0.44, and 0.58, respectively. For conventional planting, mulch cover nears zero, and figure 2 gives a subfactor of 1.0. When these subfactors were combined with the type III subfactors obtained above, a close correspondence of computed and preestablished *C*-values was obtained for crop stage 3, as shown in the table below.

All the lines in the table assume absence of plant residues on the surface and removal of the stover for silage. It should be possible to extend the analogy to high-yielding continuous corn where, for example, only the grain is harvested and the corn is planted in residues covering 75 pct of the surface. From figure 2, the type II factor would be 0.15. The adjusted canopy factor (fig. 1) would be 0.84, and the type III effect should be about equivalent to that for table line 36, which is 0.46. These three values suggest a period 3 soil-loss ratio of 0.06. Since the type II effect throughout the year largely replaces the varying type I effect, the soil-loss ratios for stages 1, 2, and 4L would also be in the neighborhood of 0.07. If corn were planted in a 90-pct cover of anchored small-grain residue, the type II factor (fig. 2) would be 0.07, and the canopy factor would lose its significance. Combined with the type III factor of 0.46, this would predict an annual *C*-value of 0.03. Based on recent minimum-tillage data, these estimates of *C* appear quite realistic for the assumed conditions.

Wheat.—For good-quality wheat an estimate of 95-pct canopy cover in crop stage 3 seems realistic. If fall height for the average drop is 0.5 m, figure 1 gives a factor of 0.20 for 95-pct canopy cover. Wheat, however, has numerous blades and stems per unit of area. Probably about half of the water intercepted by the canopy moves down the blades and stems to a point so near the ground that it regains no appreciable kinetic energy. This reduces the impact energy at the surface by about another 50 pct, leaving a canopy factor of 0.20/2, or 0.10. If the rows are with the land slope, the factor for mulch effect is still 1.0. Thus, the *C*-factor in crop stage 3 should be about 10 pct of that for crop stage 1. In lines 89, 90, 105, 106, and 107 of the handbook table, stage 3 values are very close to 10 pct of the corresponding values for stage 1, as predicted. Lines 99 and 101–104 give a range of values for crop stage 3. Applying the canopy factor of 0.10 to stage 1 values in these lines also gives stage 3 values that are within the ranges shown by the table. The larger values in the range would be predicted by assuming wheat or oats of poorer quality, and hence with less canopy effect.

HB table line No.	Corn yield (bu)	Assumed canopy (%)	Subfactors			*C*-value	
			I	II	III	Computed	HB table
1	75	95	0.34	1.0	0.30	0.10	0.10
2	75	95	.34	1.0	.34	.12	.12
33	75	95	.34	1.0	.61	.21	.22
47	75	95	.34	1.0	.70	.24	.27
3	60–74	87	.39	1.0	.36	.14	.14
4	60–74	87	.39	1.0	.38	.15	.15
34	60–74	87	.39	1.0	.65	.25	.25
48	60–74	87	.39	1.0	.75	.29	.30
5	40–59	80	.44	1.0	.41	.18	.19
35	40–59	80	.44	1.0	.71	.31	.30
49	40–59	80	.44	1.0	.78	.34	.35
7	20–35	60	.58	1.0	.52	.30	.30

Extension of the analogy to pasture, range, woodland, and idle land requires a source from which to obtain subfactor values for type III effect. Figure 3 was derived to serve this purpose until the subfactor can be evaluated directly.

The initial point (0.45) for the curves in figure 3 is an estimate of the long-term effect of no tillage and no vegetation. It was obtained from 10-yr soil-loss records on a 12-pct slope of silt loam soil that was not tilled after the first year but was kept free of vegetation and traffic. The rate of soil loss per unit of *EI* declined annually until it leveled off at about 45 pct of the rate for the first 2 yr of the study. The curvature and endpoints of the curves were based on comparisons of soil losses from meadow with those from plots having equivalent percentages of surface cover in the form of applied straw mulch. Although figure 3 is based on less firm data than desirable, its basic concepts are valid and its use in cover-factor computations has produced values that Soil Conservation Service and Forest Service personnel have found consistent with their observations.

Factor C *for Pasture, Range, and Idle Land.*—Figures 1, 2, and 3 were used with the previously described analogy technique to derive the *C*-factors given in table 2. The table provides sufficient detail for classifying canopy and surface-residue percentages on the basis of any desired grouping. The values in the table are suggested *C*-values for the universal soil loss equation, to be used with the published isoerodent map (footnote 3), soil-erodibility nomograph,[7] and slope-effect chart (footnote 3).

Derivation of a few of the values in table 2 will be described to provide a better understanding of their composition, meaning, and probable dependability.

1. The factor "0.10" in line 1, column 6: From figure 2, the factor for 40-pct mulch cover is 0.39. From figure 3, the factor for type III effect is 0.25. With no canopy, the factor for type I effect is 1.0. The product of the three subfactors is 0.10. In line 2, the close cover is weeds and undecayed plant residue. The type III effect of weeds is less than that of grass, so we use the upper curve of figure 3. The 0.39 from this curve times the 0.39 from figure 1 gives the *C*-factor of 0.15 shown in the table.

2. The factor "0.09" in line 3, column 6: The type II and type III effects are the same as for lines 1 and 2, and the subfactors are 0.39 and 0.25, respectively. Since the 25-pct canopy cover in line 3 applies only to the portion of the surface not protected by the 40-pct type II cover, figure 1 is entered with the effective canopy cover of 15 pct (0.6 of 25 pct). The adjusted subfactor for canopy effect is 0.87. The total factor *C* is $0.39 \times 0.87 \times 0.25 = 0.085$, which was rounded to 0.09 in the table.

Caution for Using Table 2. The percentages of cover shown in the headings of columns 4 to 9 include only cover by mulch or vegetation at the soil surface. Standing trees, corn plants, or stalky weeds that contact the ground only at their bases are not included in the percentages of type II cover because the sum of the cross-sectional areas of these standing stems is insignificant relative to the total land area. For dense stands of close-growing plants such as grass, the portions at the soil surface become significant and are included in the entry value for figure 2. The percentages in column 2 must be carefully distinguished from those in the headings of columns 4 to 9.

The *C*-values in tables 2 and 3 are for sheet and rill erosion. If gullying is significant, sediment from the gullies must be computed separately.

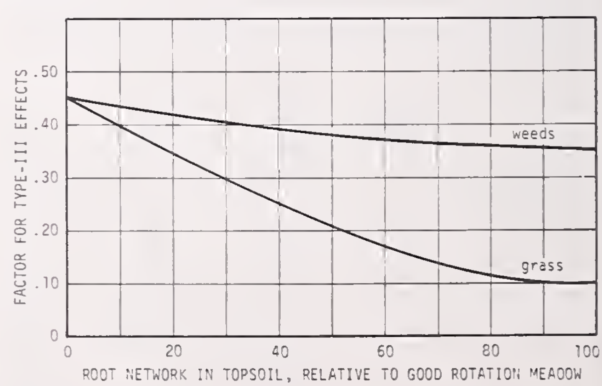

Figure 3.—Type III effects of undisturbed land areas on *C*-factor. These values do not apply to cropland and construction sites.

[7] Wischmeier, W. H., Johnson, C. B., and Cross, B. V. 1971. A soil erodibility nomograph for farmland and construction sites. Journal of Soil and Water Conservation 26: 189–193.

TABLE 2.—*C-values for permanent pasture, rangeland, and idle land*[1]

Canopy: Type and height[2] (1)	Canopy: Pct cover[3] (2)	Ground cover: Type[4] (3)	Pct cover: 0 (4)	20 (5)	40 (6)	60 (7)	80 (8)	95–100 (9)
None	...	G	0.45	0.20	0.10	0.042	0.012	0.003
		W	.45	.24	.15	.091	.043	.011
Weeds or short brush (0.5 m).	25	G	.36	.17	.09	.038	.013	.003
		W	.36	.20	.13	.083	.041	.011
	50	G	.26	.13	.07	.035	.012	.003
		W	.26	.16	.11	.076	.039	.011
	75	G	.17	.10	.06	.032	.011	.003
		W	.17	.12	.09	.068	.038	.011
Brush or bushes (2 m).	25	G	.40	.18	.09	.040	.013	.003
		W	.40	.22	.14	.087	.042	.011
	50	G	.34	.16	.08	.038	.012	.003
		W	.34	.19	.13	.082	.041	.011
	75	G	.28	.14	.08	.036	.012	.003
		W	.28	.17	.12	.078	.040	.011
Trees, no low brush (4 m).	25	G	.42	.19	.10	.041	.013	.003
		W	.42	.23	.14	.089	.042	.011
	50	G	.39	.18	.09	.040	.013	.003
		W	.39	.21	.14	.087	.042	.011
	75	G	.36	.17	.09	.039	.013	.003
		W	.36	.20	.13	.084	.041	.011

[1] All values assume (1) random distribution of mulch or vegetation, and (2) mulch of substantial depth where credited.

[2] Classified by average fall height of waterdrops from canopy to soil surface, in meters.

[3] Percentage of total-area surface that would be hidden from view by canopy in a vertical projection.

[4] G—Cover at surface is grass or decaying, compacted duff of substantial depth. W—Cover at surface is weeds (plants with little lateral-root network near the surface) or undecayed residue.

Factor C for Woodland.—Permanent woodland differs in several respects from the situations covered by table 2. An accumulation of compacted decaying duff several inches thick is more effective than a mulch of fresh straw. The limited existing data support a *C*-value as low as 0.001 for woodland with a 100-pct cover of such duff. For incomplete duff covers, *C* is obtained by taking a weighted average of the values for the duff-covered portion and the other portion.

For the portion that does not have a litter cover of appreciable depth, additional factors must be considered. If randomly distributed litter-covered areas comprise at least half of the total area, an effect similar to that of contour strip cropping should be at least equivalent to the strip crop factor of 0.5 that is applied on cropland where meadow and a row crop are alternated in contoured strips. This is because much of the soil detached from the no-mulch spots is filtered out as the runoff crosses the heavy-duff areas. Also, soil organic-matter levels are usually much higher on permanent woodland than on comparable cultivated soil. The increased soil organic matter coupled with the root growth should justify use of the lower curve of figure 3 for type III effect even though the undergrowth is not sod-forming grass.

Table 3 presents *C*-values for specified woodland conditions, computed by combining these factors as illustrated below.

The lowest *C*-factor listed in the line of table 3 that represents medium stand with managed undergrowth is calculated on the basis that 90 pct of the area has a litter cover. The areas without litter cover are assumed to be under the major

TABLE 3.—*C-factors for woodland*

Stand condition	Tree canopy (pct of area)[1]	Forest litter (pct of area)[2]	Undergrowth[3]	*C*-Factor
Well stocked	100–75	100–90	Managed[4]	0.001
			Unmanaged	.003–0.011
Medium stocked	75–40	90–75	Managed	.002– .004
			Unmanaged	.01– .04
Poorly stocked	40–20	70–40	Managed	.003– .009
			Unmanaged	[5].02– .09

[1] Area with tree canopy over less than 20 pct will be considered grassland or cropland for estimating soil loss (table 2).

[2] Forest litter is assumed to be of substantial depth over the percent of the area on which it is credited.

[3] Undergrowth is defined as shrubs, weeds, grasses, vines, etc. on the surface area not protected by forest litter. Usually found under canopy openings.

[4] Managed—Grazing and fires are controlled. Unmanaged—Stands that are overgrazed or subjected to repeated burning.

[5] For unmanaged woodland with litter cover of less than 75 pct, *C*-values should be derived by taking 0.7 of the appropriate values in table 2. The factor of 0.7 adjusts for the much higher soil organic matter on permanent woodland.

open spots in the tree canopy. If, for these spots, we assume a 95-pct cover of undergrowth with a drop fall height of 0.5 m, we have from figure 1 a canopy factor of 0.20, and from figure 3 a factor of 0.10. From the preceding paragraph we have a strip crop factor of 0.5. The *C* for the 10 pct of the total area that is in this category is then $0.2 \times 0.1 \times 0.5 = 0.01$. For the 90 pct of the area that has a heavy duff cover, the factor is 0.001, as indicated above. The weighted-average *C* for the entire area is then $(0.10 \times 0.01) + (0.90 \times 0.001) = 0.002$. This is the minimum *C* for the range of conditions represented by this line in the table. For the other end of the range, the assumptions are no litter cover on 25 pct of the area, and an 85-pct canopy of managed undergrowth. For this condition, *C* is $0.29 \times 0.1 \times 0.5 = 0.0145$, and the weighted average would be $(0.25 \times 0.0145) + (0.75 \times 0.001) = 0.004$. For the unmanaged woodland, both the undergrowth cover and the duff cover would be less, and computed *C*-values would be higher.

For the poorly stocked and unmanaged woodlands, more specific values within the 0.02 to 0.09 range shown by table 3 can be obtained from table 2. For example, a 25-pct tree canopy and 40-pct litter cover would be described by line 9, column 6, of table 2. This suggests a *C* of 0.09. If the situation were permanent woodland, the factor 0.7 described in footnote 5 of table 3 would reduce this *C*-value to 0.063.

CONCLUSION

Tables of cover-factor values for various qualities of range, meadow, and woodland were derived by an objective analogy method. The analogy was facilitated by subdividing the soil loss equation *C*-factor into raised-canopy, surface-contact, and beneath-surface effects, and deriving relationships for evaluating each effect as a subfactor. The *C*-value tables are not presented as firm research data but as the best estimates now available for use in computing the contributions of undisturbed lands to watershed sediment yield.

SEDIMENT-YIELD CHARACTERISTICS FROM UNIT SOURCE WATERSHEDS[1]

By Edd D. Rhoades, Norman H. Welch, and Gerald A. Coleman[2]

INTRODUCTION

For nearly 40 years, Federal, State, and local governments and individuals have been working cooperatively to reduce soil erosion on agricultural and other lands. The program has been successful in protecting millions of acres from accelerated erosion. However, much remains to be done, since sediment is still the largest single pollutant of our streams and lakes. The term "sediment" in this paper is restricted to the material moved by natural and man-accelerated processes of erosion of soils and geologic materials.

Presently, watershed sediment models are needed to develop sediment-routing procedures, improve sediment-yield prediction for reservoir design, and assess the impact of watershed cultural practices and other changes, including urbanization. The development of such models depends upon an adequate quantity of sediment-yield data from various land uses, soil types, and areas of different rainfall characteristics. The sediment data collection program described herein was initiated to aid in the development of sediment-yield prediction models.

The purpose of this report is to compare some preliminary data relative to sediment yield from several small watersheds subjected to different land use. Because the data recorded were for a short (1967–71) and generally dry period, they are insufficient for developing a dependable model. However, the data do show many interesting features of sediment yield. These include the relative yield of good-to-excellent rangeland versus poor-to-fair rangeland, sheet and rill erosion from poor-to-fair rangeland versus gully erosion from poor-to-fair rangeland, and the magnitude and seasonal distribution for different cropping patterns.

WATERSHED DESCRIPTION

Research began in 1966 on the rainfall-runoff-sediment yield relationship from several unit source watersheds at the Southern Great Plains Watershed Research Center near Chickasha, Okla. These watersheds include rangeland, gullied areas, irrigated and dryland row crops, and small grain and hay crops.

Rangeland

The four rangeland watersheds, ranging from 18 to 27 acres, are all within 1 mi^2. Two of these watersheds, R-5 and R-6, are virgin grassland in good-to-excellent condition, with no evidence of active gullies. Although no attempt has been made to regulate grazing on these areas, the stocking rate has generally been within the recommended limits during the past decade. The principal soils are Renfro silt loam and Grant silt loam. In addition to being within the same fenced enclosure, they are adjacent to each other and are subject to essentially the same management practices. The other two grassland watersheds, R-7 and R-8, are in poor-to-fair condition. They were cultivated from about 1900 until 1940, when they were returned to rangeland use because of severe erosion. Through natural plant succession and reseeding, a fair-to-good stand of native little bluestem (*Andropogon scoparius* Michx.) grass now covers a major portion of

[1] Cooperative research of the Agricultural Research Service, U.S. Department of Agriculture, and the Oklahoma Agricultural Experiment Station, Stillwater, Okla.

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these watersheds. Numerous severely eroded areas, which support annual weeds and grasses, exist around the perimeter of the watersheds. Although both watersheds are within the same fenced enclosure, watershed R-7 is normally grazed slightly more than R-8. During recent years, both have been slightly overgrazed.

Watersheds R-7 and R-8 also have an active gully system. The bottom of the principal gully in each watershed consists primarily of sandstone. The gradient offers little chance of establishing a vegetative cover sufficient to trap sediment in the gully itself. By 1970 the gully in watershed R-7 had advanced to a point where about 50 pct of the drainage area was below the gully overfall. In an effort to determine the magnitude of sediment yield from gully erosion, an intermediate gaging station was installed at the overfall.

Cropland

The seven cropland watersheds, ranging from 13 to 44 acres, are located on the South Central Oklahoma Research Station and are within 1 mi^2. The watersheds are on the alluvium of the Washita River, with land and channel slopes ranging from less than 0.05 to 0.15 pct. The soils are a mixture of McLain silt loam, McLain silty clay loam, and Reinach silt loam. All of these watersheds have been leveled for row irrigation or graded for surface drainage. Farming operations are controlled and implemented by the Oklahoma Agricultural Experiment Station.

INSTRUMENTATION AND CLIMATE

Thiessen weighted precipitation amounts for each watershed were obtained from two recording rain gages. All runoff measuring stations were precalibrated H-flumes or concrete V-notch weirs equipped with FW-1 stage recorders. Sediment samples were collected with Chickasha sediment samplers[3] at 7 of the 12 locations and by hand at the other 5 locations. Sediment yield was computed from suspended-sediment concentrations and flow rates at numerous time intervals during each runoff event.

Rainfall is not well distributed throughout the year, and droughts are common. Rainstorms during spring and early fall tend to be larger and of greater intensity than at other times. The 30-yr average precipitation at Chickasha, Okla., from 1930 to 1960, was 31.60 inches, with one-half of this amount falling during the 4 months of May, June, September, and October. Precipitation on these watersheds during 1967–71 was substantially less than the 30-yr normal. A low of 19.75 inches and a high of 33.72 inches were measured, with a period average of 26.97 inches for all watersheds. Precipitation on the rangeland watersheds averaged 28.94 inches, whereas the precipitation on the cropland watersheds averaged only 25.84 inches.

EXPERIMENTAL DATA AND RESULTS

Rangeland

Annual values of precipitation, runoff, and sediment yield from the four grassland watersheds during 1967–71 are given in table 1. Values from the two virgin grassland watersheds, R-5 and R-6, which were in good-to-excellent condition, are similar. The 5-yr average annual rainfall for watersheds R-5 and R-6 was 29.38 inches and 29.35 inches, respectively. Average annual runoff and sediment yield were 0.99 inch with 54 lb/acre from watershed R-5 and 0.93 inch and 93 lb/acre from watershed R-6. The sediment yields are probably normal for good-to-excellent native grass ranges in this locality, where there are no bare areas or active gullies.

The precipitation values for the formerly cultivated grassland watersheds, R-7 and R-8, were about equal, with an average annual runoff of 4.41 and 4.07 inches, respectively. Although the overall grass cover was slightly better on watershed R-8 than on R-7, the gullies were more extensive on R-8. This may partly account for some of the observed differences in runoff. The average annual sediment yield from watershed R-7 was 5,300 lb/acre, compared to 11,900 from watershed R-8. This was a loss of 1,200 and 2,900 lb/acre-inch of runoff, respectively. The above quantities include sediment that was measured in the runoff water passing the gaging station, and sediment that was deposited immediately upstream of the gaging station. Periodic cross-

[3] Miller, Gary E., Allen, Paul B., Welch, Norman H., and Rhoades, Edd D. 1969. The Chickasha sediment sampler. U.S. Department of Agriculture, Agricultural Research Service, ARS 41-150, 14 pp.

TABLE 1.—*Rainfall, runoff, and sediment yield from rangeland watersheds, 1967–71*

Watershed	R-5			R-6			R-7			R-8		
Acres	23.72			27.22			19.19			18.46		
Condition	Good-to-excellent			Good-to-excellent			Poor-to-fair			Poor-to-fair		
	P (in)	Q (in)	S (lb/acre)	P (in)	Q (in)	S (lb/acre)	P (in)	Q (in)	S (lb/acre)	P (in)	Q (in)	S (lb/acre)
1967	27.98	1.12	89	27.94	1.20	114	27.01	3.77	2,273	27.44	2.96	3,077
1968	31.24	.30	24	31.54	.28	28	30.69	4.65	1,558	31.53	3.51	3,369
									[1]3,075			[1]15,648
1969	28.99	1.39	103	29.13	1.22	200	26.94	3.98	4,560	28.11	4.48	7,349
									[2]2,771			[2]7,476
1970	24.95	.35	12	24.92	.34	18	23.98	2.92	2,415	24.15	3.00	3,333
									[2]1,800			[2]4,426
1971	33.72	1.78	41	33.21	1.64	104	32.96	6.72	3,800	32.21	6.41	8,275
									[2]4,234			[2]6,672
Average	29.38	.99	54	29.35	.94	93	28.32	4.41	[3]5,300	28.69	4.07	[3]11,900

P Precipitation. Q Runoff. S Sediment yield. [1] Sediment deposited upstream from weir during 1967 and 1968.
[2] Annual amount of sediment deposited upstream from weir. [3] Includes total discharged and deposited sediment.

sectional surveys were made to calculate amounts of sediment deposited in the 150-ft reach directly upstream of the gaging station. The more extensive gully system in watershed R-8 was probably the primary cause for the difference in sediment yield from the two areas.

A comparison of the virgin grassland watershed R-5 with the eroded grassland watershed R-7 shows 4.4 times as much runoff and 100 times as much sediment yield from the eroded area than from the virgin area. Differences in rainfall were small and would not account for the disparity in sediment yield.

To determine the magnitude of gully erosion on the eroded grassland watershed R-7, an additional gaging site was established at the overfall in 1970. This subdivision made it possible to separate the amount of sediment produced in the nongullied portion of the watershed from that of the 0.15-acre gullied portion. A preliminary estimate of sediment production from the gullied portion of watershed R-7 was determined with the 1971 data. During 1971, runoff from the upper 9.30 acres of watershed R-7 was 8.29 inches, and the sediment yield was 3,960 lb/acre (2 tons/acre). By assuming that the sediment loss rate from sheet and rill erosion for the 9.74 acres of the lower portion of the watershed was the same as that for the upper portion, the sediment produced from the 0.15 acre of gullied area was calculated as 78,700 lb, or 527,000 lb/acre (268 tons/acre). Thus, less than 1 pct of the total area of the eroded grassland watershed produced 51 pct of all sediment from the watershed. Because of a slightly thicker grass cover on the lower nongullied area than on the upper nongullied area, the calculated sediment yield from the gully is probably conservative.

Cropland

Annual values of precipitation, runoff and sediment yield from the seven cropland watersheds for the period 1967–71 are given in table 2. Average annual sediment yield from watershed C-1, in continuous dryland cotton for the 5-yr period, was 770 lb/acre. This value may be unrepresentatively low because the main drain in the field has a slope of less than 0.05 pct, which allows most of the sands and heavy silt fractions from steeper portions of the watershed to settle out before reaching the measuring station.

TABLE 2.—*Rainfall, runoff, and sediment yield from cropland watersheds, 1967–71*

Crop	Dryland cotton			Irrigated cotton			Irrigated cotton			Continuous wheat		
Watershed	C-1			C-3			C-4			C-5		
Acres	17.83			44.26			29.93			12.75		
	P (in)	Q (in)	S (lb/acre)	P (in)	Q (in)	S (lb/acre)	P (in)	Q (in)	S (lb/acre)	P (in)	Q (in)	S (lb/acre)
1967	26.76	0.08	39	25.60	2.50	2,511	25.55	1.39	1,207	24.80	1.32	267
1968	32.10	2.29	1,249	29.74	3.99	5,642	29.97	2.82	3,692	29.22	.60	35
1969	24.54	1.84	1,220	23.57	1.72	1,960	23.80	1.48	1,100	23.36	.72	60
1970	21.19	1.57	422	21.04	3.43	1,994	21.18	2.25	2,168	20.15	.70	412
1971	30.97	4.39	923	30.31	5.01	4,361	29.98	3.88	3,663	29.68	2.42	1,875
Average	27.11	2.03	771	26.05	3.33	3,294	26.10	2.36	2,366	25.44	1.15	530

Crop	Continuous wheat			Mixed crops			Alfalfa-wheat rotation		
Watershed	C-6			C-7			C-8		
Acres	13.00			26.52			27.28		
	P (in)	Q (in)	S (lb/acre)	P (in)	Q (in)	S (lb/acre)	P (in)	Q (in)	S (lb/acre)
1967	24.66	1.19	292	24.38	1.91	1,199	24.19	0.57	9
1968	29.18	1.14	145	28.89	2.15	1,781	29.08	.17	6
1969	23.29	1.05	80	23.13	2.20	1,200	23.27	.16	40
1970	19.92	.99	794	19.75	1.92	902	20.12	.69	68
1971	29.78	3.04	3,519	29.85	3.86	8,176	31.53	1.60	2,115
Average	25.37	1.48	966	25.20	2.41	2,652	25.64	.64	448

P Precipitation. Q Runoff. S Sediment yield.

Watersheds C-3 and C-4 have been planted to irrigated cotton crops since 1964. Watershed C-3 is divided into three subplots with a tail-water drainage channel at the lower end of each subplot, whereas watershed C-4 consists of only one plot with the main tail-water drainage channel across the lower end. Normally, about 12 inches of irrigation water is applied during July and August, with none lost as runoff. Although slopes are about 0.15 pct, the areas are well drained. Normal tillage includes moldboard plowing 8 to 10 inches deep in mid-December, with areas left rough until mid-March when the seedbed is prepared. Cotton on these watersheds is usually planted in mid-May; thus, a clean, smooth, freshly tilled seedbed exists during most of the spring rainy season. The major portion of the sediment movement from these watersheds occurs during spring. For example, the storm of May 31, 1971, caused 1.02 inches of runoff and 2,600 lb/acre of sediment yield from watershed C-3. A larger rainfall event on October 2, 1971, caused 1.74 inches of runoff but only 520 lb/acre of sediment yield.

Watersheds C-5 and C-6 have been in continuous dryland wheat since 1964. Construction of a main drainage channel in 1964 along one side of each watershed has improved the surface drainage; however, approximately 20 pct of each watershed is poorly drained. Soon after wheat harvest in mid-June, each of these watersheds is normally disked or plowed 8 to 10 inches deep. The area is left rough and cloddy until the latter part of August, when the wheat seedbed is prepared; planting follows in early October. Unlike the cotton land, the wheat areas are bare during the fall, but well covered during the spring; thus, the major sediment yield from these watersheds occurs during the fall. This is exemplified by data from wheatland watershed C-5 and the same two rainfall events discussed before. The storm of May 31, 1971, produced only 0.18 inch of runoff and 8 lb/acre of sediment, whereas the storm of October 2, 1971, produced 1.76 inches of runoff and 2,754 lb/acre of sediment.

Watershed C-7 has been in row crops and sown sudan and alfalfa since 1964. The area is divided into two nearly equal subplots. It has been graded and leveled and has an average slope of approximately 0.15 pct. During 1967, the entire watershed was planted in cotton, grain sorghum, and soybeans. In 1968, the lower portion was planted in cotton, grain sorghum, and soybeans, whereas the upper portion was summer-fallowed and planted in alfalfa in September. From 1969 through 1971, the upper portion remained in alfalfa. In 1969–70, the lower portion was in cotton, grain sorghum, and soybeans. The majority of the lower portion was summer-fallowed during the spring and summer of 1971 and then planted in alfalfa in mid-September. Runoff and sediment production was less than that recorded on the irrigated, row-cropped watersheds during the first 4 yr, but much greater the fifth year, when approximately one-half of this area was fallowed during the spring and summer.

Watershed C-8 was in alfalfa from the fall of 1965 until the summer of 1969, when it was plowed. The watershed has been in continuous wheat since the fall of 1969. The average annual runoff and sediment yield during the 3 yr of alfalfa was only 0.30 inch and 13 lb/acre, respectively. The major runoff and sediment yield during the period of record occurred on October 2, 1971, when a runoff of 1.46 inches produced 2,046 lb/acre of sediment. This storm occurred when the area was freshly plowed, just before wheat was planted.

SEDIMENT MOVEMENT FROM LOESSIAL WATERSHEDS[1]

By R. F. Piest, L. A. Kramer, and H. G. Heinemann[2]

INTRODUCTION

The loess-mantled region bordering the Missouri River from South Dakota into Missouri is subject to extensive erosion from surface runoff. The favorable climate and the natural fertility of the deep, moderately permeable soil renders the region exploitable for intensive agriculture, even though the terrain is steep enough to cause high erosion rates during intense rainstorms. The erosion processes, if not impeded, deplete soil fertility by removing the humus-enriched topsoil. But even more serious aspects of erosion are (1) dissection of the land surface by rills and gullies and (2) downstream damage by deposition of sediments and sediment-borne agricultural chemicals. Fortunately, the quantities of soil eroded from fields and drainageways of the loessial region each year are not moved en masse to the Mississippi River and thence to the Gulf of Mexico. On the average, such a trip requires a decade or more in an unregulated drainage system. Regardless of regulation, it is necessary to know the amount and location of these sediments to efficiently design and operate water resource and soil conservation systems.

The purpose of this study is to review what is known about the movement of soils from loessial watersheds and to extend this knowledge by applying experiences from instrumented watersheds near Treynor, Iowa. We examine inaccuracies resulting from the use of the sediment-delivery method to predict sediment yields in the loess region. Then, using previously defined relationships between soil erosion and sediment yield—and insights gained from the intensive measurements on the Treynor watersheds—we identify factors that will improve soil loss predictions and propose an independent function to represent sediment conveyance/retardance properties of a soil surface. The end result, when fully developed, should improve sediment-yield prediction procedures.

PROCEDURES FOR ESTIMATING EROSION RATES AND SEDIMENT MOVEMENT

Sediment-yield estimating procedures for the loessial region have been developed (directly and indirectly) from measurements at experiment-station erosion plots at Clarinda and Castana, Iowa, and Bethany, Mo.; from streamflow sampling stations operated by the U.S. Geological Survey and the Corps of Engineers; and from reservoir sedimentation surveys by several Federal agencies. These measurements have been widely utilized, some of them beyond the specific purpose for which they were developed. Many interpretations and empiricisms have also evolved from the data to make the information more generally applicable to the many design problems confronting conservationists. Gottschalk and Brune (*3*)[3] used the work of Musgrave and others to develop an expression for predicting sediment accumulation in reservoirs. These sedimentation-rate estimates were required for the design of many small detention and desilting reservoirs. Glymph (*2*) added

[1] Cooperative research of the Agricultural Research Service, U.S. Department of Agriculture, and the Agriculture and Home Economics Experiment Station, Ames, Iowa.

[2] Hydraulic engineer, agricultural engineer, and hydraulic engineer, respectively, North Central Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, Columbia, Mo. 65201.

[3] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this paper.

streamflow sediment records to Gottschalk's reservoir data to relate watershed sediment yields to gross erosion, number of rainfall events equal to or exceeding 1 inch/d during the growing season, and watershed size.

Similar developments have continued, and the conservationist can now select whichever of the following prediction methods best suits his requirements.

1. *Streamflow sampling method,* in which streamflow samples are used to predict sediment discharges: A relationship between sediment discharge and runoff is usually obtained by concurrent field measurements. It is necessary to sample the full range of variation in these factors for maximum reliability, but more often some synthesis is required. Once the long-term runoff-sediment relation is established, it is combined with long-term flow-frequency data to obtain long-term sediment yields. This method is probably the most costly and time-consuming field mensuration program, but the storm data permit insights into erosion processes that are impossible to gain with other methods.

2. *The reservoir sedimentation survey method,* in which accumulated sediment volumes and weights and reservoir trap efficiencies are analyzed for useful general information on sediment yields in a region: Less field work is required in this method, but the data are not as easily adjusted for special or unusual conditions as is the sediment-rating curve method based on streamflow samples.

3. *The sediment-delivery method,* in which the sediment yield to some downstream cross section or deposition point is based on an estimate of total upstream erosion rates and an estimate of the portion of this total that appears downstream: Sediment yields from methods 1 and 2 and computations of total (gross) erosion for a given region form the bases for determining a sediment-delivery percentage or ratio. This method is an excellent qualitative tool for pinpointing sedimentation problem areas and for designing conservation structures. But the quantitative accuracy of the method, at present, is questionable.

4. *Methods based on empirical equations* derived from measured sediment yields (methods 1 and 2) and watershed hydrologic characteristics: Most of these empirical expressions have severely limited application, even in the region of origin, because the physical laws governing sediment movement are ill-defined.

5. *Methods based on equations,* nearly all empirical, which express sediment transport in terms of the hydraulic and sediment properties of alluvial channels: These methods are often applied when most of the material eroded from the watershed is sand size or larger and can be found in appreciable quantities in the streambed and when there is appreciable channel erosion. These methods are not applicable for many small watersheds in the Missouri Valley loess area.

6. *The simulated-watershed sediment model,* which portrays the kinematics of sediment transport through a watershed, from point of origin to deposition, in response to a given rainfall or runoff input: This method is still essentially undeveloped.

Beer et al. (*1*) measured the sediment characteristics of 24 reservoir watersheds in Iowa and Missouri to test sediment-prediction techniques applicable to the loess region. They stated: "Most techniques are empirical and require considerable judgment on the part of the designer." They also concluded that (1) drainage area and sediment-delivery ratio are poorly correlated (a good correlation is needed, of course, to apply the sediment-delivery method) and (2) the estimates of sheet-rill erosion rates for the watersheds in the region contributed the most variation to the predicted sediment yield. Sediment yields from reservoir surveys and trap efficiency estimates were among the most accurately determined variables of their study.

Of the foregoing methods, the sediment-delivery method is used most in operational programs for farm conservation and watershed treatment. Equations for estimating sheet-rill erosion, principally the so-called Musgrave equation (*6*) and universal soil loss equation (*12*), contain such rational factors as climate, topography, soil, land use, and land treatment and are backed by considerable data from experiment-station plots. If the mechanisms causing sediment movement along a watershed surface can be better described, the sediment-delivery method has great potential, in the immediate future, for predicting sediment yields. In the long term, such information is needed to develop watershed sediment models.

The sediment-delivery ratio, D, or percentage, $100D$, is a measure of the diminution of eroded sediments, by deposition, as they move from the erosion sources to any designated downstream location. The formula is

$$D = Y/T \qquad (1)$$

where Y=the sediment yield at the downstream location

and T=the total (gross) erosion, which includes gully, channel, and sheet-rill erosion above that location.

In the application of the sediment-delivery method, $Y = DT$; D is usually obtained from a graphical relation with watershed size. For most design problems, the foregoing equation is considered valid for long-term average annual conditions but much less applicable for shorter periods. The accuracy of the sediment-delivery method could be much improved by insights obtained from an analysis of storm-to-storm variations in sediment delivery. We will show sediment-delivery relationshps, by storm and by season, in simplified form by considering only the sheet-rill erosion component. This component was obtained at the Treynor watersheds by sampling streamflow from the outflow drainageways just upstream of the gully heads. The effect of the simplification will be discussed later.

Figure 1 is reproduced from Beer et al. (*1*) to show the extreme variability found in sediment delivery-area relations. Curve *A* represents about 30 small reservoir watersheds scattered throughout the Missouri River Basin-loess hills region; curve B was taken from unpublished data for Mule Creek basin in southwest Iowa, where the measured sediment deposition exceeded computed erosion rates in several instances. The plotted points represent a study of 24 reservoir watersheds in western Iowa and northwest Missouri surveyed by Beer et al. (*1*) and support their statement that sediment-delivery percentage is poorly correlated with drainage area. The Musgrave equation, which was used to evaluate sheet-rill erosion rates, was the basis for the sediment-delivery calculations. We will try to explain the variability in the sediment delivery-drainage area relation by examining annual and storm sediment data from the loessial watersheds near Treynor, Iowa.

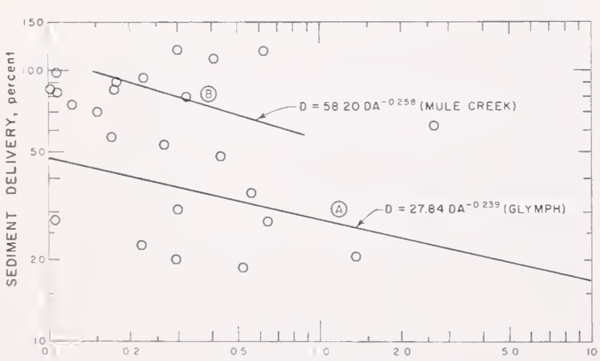

FIGURE 1.—Comparison of computed sediment-delivery percentages for 24 reservoir watersheds with curves developed from reservoir data from eastern Nebraska and western Iowa. After Beer et al. (*1*); curve *A* from Glymph (*2*).

Table 1 is a summary of annual rainfall erosivity parameters (*11*), 1965–71, and measured sediment yields from sheet-rill sources from 74- and 83-acre, contour-planted, continous-corn watersheds 1 and 2 near Treynor, Iowa. Table 2 is a summary of rainfall erosivity, runoff, computed sheet-rill erosion, measured sediment yield, and computed sediment-delivery percentages by storm, for watershed 1.

Sediment-Delivery Interpretations—Annual Basis

The mean annual rainfall on the watersheds for 1965 through 1971 (table 1) was nearly 4 inches above the long-term average of 28.6 inches/yr recorded at nearby Omaha, Nebr., but the computed rainfall erosivity was 80 pct higher than the long-term regional value. The annual sediment-delivery values ranged from 4 to 72 pct, with a 7-yr mean of 46 pct. Apparent reasons for year-to-year variations in the sediment-delivery are the amount of rainfall and the seasonal distribution of rainfall erosivity; the wet years of 1965 and 1967 had the highest sediment delivery, whereas the driest years, 1966 and 1971, had the lowest erosivities but sediment-delivery values close to the mean.

Apparent discrepancies in table 1, such as the wide variation in sediment-delivery values for comparable rainfall in 1969, 1970, and 1971, can

TABLE 1.—*Annual sheet-rill erosion, sediment yield, and percentage delivery from contour-corn watersheds 1 and 2 at Treynor, Iowa, 1965–71*

Year	Rainfall (inches)		Kinetic energy (ft-tons/acre-inch)		Rainfall erosivity factor (100R)[1]		Sheet-rill erosion (tons/acre) by universal equation[2]		Measured sediment yield (tons/acre) from sheet-rill erosion		Sediment delivery (pct)	
	W-1	W-2	W-1	W-2	W-1	W-2	W-1	W-2	W-1	W-2	W-1	W-2
1965	45.3	44.3	30,700	27,700	40,600	36,900	72.0	54.6	44.0	36.4	61	67
1966	20.3	20.5	10,700	11,000	11,900	12,000	24.8	20.9	6.7	8.6	27	41
1967	38.2	37.6	27,100	26,700	60,400	59,800	137.3	113.7	99.1	75.2	72	66
1968	32.3	32.5	19,600	18,600	27,500	27,000	45.1	36.5	3.7	4.1	8	11
1969	31.4	31.5	18,300	18,700	18,200	19,500	32.7	28.5	1.8	1.0	6	4
1970	31.5	30.8	20,200	19,200	36,800	30,400	55.7	37.9	11.8	7.4	21	20
1971	28.9	29.0	16,800	16,500	18,800	16,500	41.8	28.2	20.0	13.3	48	47
Mean ..	32.6	32.3	20,500	19,800	30,600	28,900	58.5	45.8	26.7	20.9	46	46

[1] Long-term *R*-factor for region is 160; $100R = 16{,}000$. [2] See reference *11*.

be partially explained by consideration of the magnitude and seasonal occurrence of the rainfall erosivity variable of the universal soil loss equation. Figure 2 shows that 1969 and 1971 rainfall erosivities were similar and just slightly above the long-term average. However, the largest 1969 storms occurred on July 17 and August 20, whereas the 1971 storms were concentrated on several days in May and June. As a result of crop-cover differences on these dates, the computed sheet-rill erosion rates for 1969 and 1971 differed somewhat, being 32.7 and 41.8 tons/acre, respectively; but the measured sediment yields were vastly different—1.8 and 20.0 tons/acre. The effective erosivity of the rainfall, tempered by the existence of the crop canopy during the growing season (*11*), is shown in figure 3.

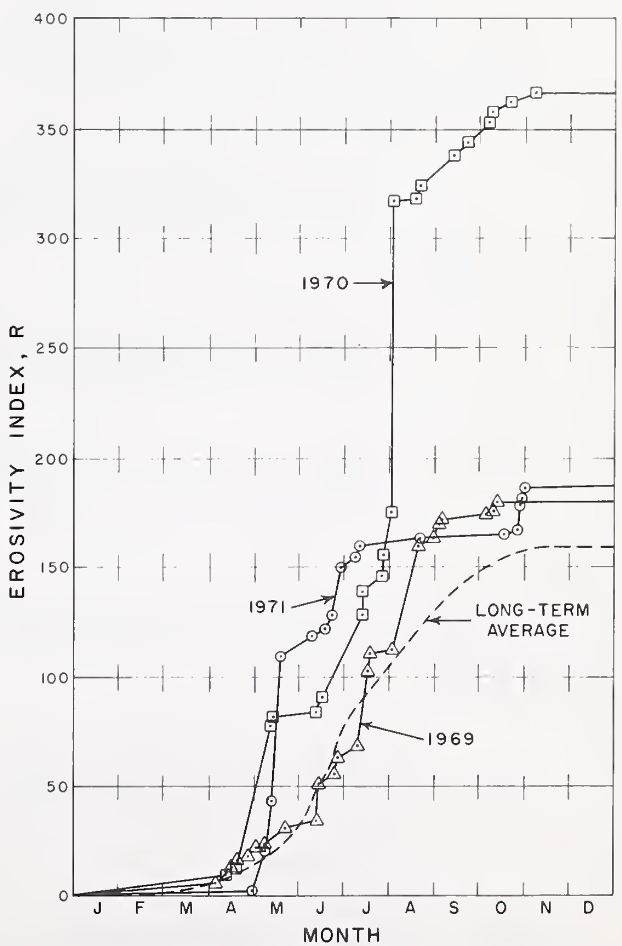

FIGURE 2.—Rainfall erosivity variation at watershed 1 during 3 consecutive years of comparable total rainfall.

TABLE 2.—*Sediment-delivery and associated information for well-sampled runoff events at watershed 1, 1965–71*

Date	Precipitation[1] Amount (inches)	Precipitation[1] Kinetic energy (ft-ton/acre-inch)	Precipitation[1] Erosivity (R)	Runoff Duration From (24-h clock)	Runoff Duration To (24-h clock)	Runoff Amount (inches)	Runoff Peak (ft^3/s)	Antecedent soil moisture, 0"–6" depth (inches)	Computed soil loss[2] (tons/acre)	Measured sediment yield (tons/acre)	Sediment delivery (pct)
1965											
May 17	0.97	947	1,724	2345	0217	0.20	66	1.80	4.55	3.81	84
May 22	.54	479	460	0001	0132	.39	167	2.50	1.22	6.76	554
May 22	.40	310	161	0132	0400	.17	29	2.50	.42	.92	219
May 22	.25	202	83	1446	1700	.14	47	2.50	.22	1.26	573
May 24	.74	664	857	1741	2030	.28	94	2.40	2.26	3.01	133
May 25	.33	300	174	2105	2247	.11	38	2.40	.46	1.19	259
May 26	.10	57	6	0041	0209	.02	3	2.30	.02	.02	100
June 2	.43	344	227	0352	0500	.03	8	2.10	.60	.12	20
June 6	.68	654	693	1721	1852	.37	92	2.05	1.83	2.39	131
June 28	.62	658	829	2248	2327	.10	44	2.00	1.79	1.11	62
June 28	1.22	1,295	3,134	2327	0021	.51	104	2.40	6.76	4.58	68
June 29	.34	325	247	0021	0101	.13	44	2.50	.53	.69	130
July 1	.17	152	49	1855	2045	.06	24	2.30	.10	.24	240
Aug. 29	1.37	1,373	2,800	2337	0140	.15	27	1.45	3.25	.24	7
Aug. 30	.47	435	396	0140	0400	.07	20	1.70	.46	.07	15
Sept. 7	1.27	1,304	2,660	0111	0225	.28	69	2.40	3.08	.32	10
Sept. 7	.54	480	413	0401	0506	.12	27	2.50	.48	.10	21
Sept. 7	.85	801	1,081	0506	0745	.30	46	2.50	1.25	.26	21
Sept. 8	.32	280	157	0600	0800	.12	27	2.50	.18	.16	89
1966											
June 5	.88	850	1,368	0345	0526	.08	21	2.08	3.61	1.01	28
June 25	.51	532	660	2308	0040	.05	21	2.50	1.42	.50	35
June 26	.99	996	1,683	0200	0344	.36	147	2.50	3.64	4.69	129
1967											
June 4	3.60	3,415	7,513	2328	0600	1.79	145	2.30	19.84	15.40	78
June 7	1.62	1,765	5,542	1659	1902	1.23	411	2.50	14.63	13.70	94
June 7	.70	584	537	1902	2400	.45	83	2.50	1.42	1.92	135
June 9	.49	466	466	0114	0155	.35	117	2.40	1.23	2.08	169
June 9	.44	377	219	0155	0339	.30	96	2.50	.58	1.60	276
June 9	1.51	1,401	2,914	2044	0200	1.16	212	2.50	7.69	7.38	96
June 11	.93	729	598	2005	0121	.51	113	2.50	1.58	1.73	110
June 14	.86	822	1,085	0523	0809	.50	235	2.40	2.86	3.06	107
June 15	.51	429	279	2026	2200	.19	60	2.23	.60	.81	135
June 20	6.03	6,543	32,584	2104	2400	4.21	438	2.20	70.38	49.70	71
1968											
June 10	.88	868	781	2224	0130	.04	12	1.75	2.06	.38	18
June 13	.90	933	1,838	2139	0025	.21	67	2.11	4.85	2.56	53
July 30	1.48	1,561	4,340	2135	2400	.04	8	1.00	9.38	.08	1
Oct. 16	3.03	2,771	4,849	1842	0030	.40	27	2.00	5.62	.12	2

1969										
Apr. 16	1.05	801	577	0230	0743	.04	1	2.30	1.04	.05	5
June 26	.57	557	646	1135	1300	.02	6	2.15	1.40	.08	6
July 17	2.11	1,943	2,448	0558	1032	.17	28	1.65	5.29	.48	9
1970											
May 12	1.65	1,760	5,104	0007	0130	.43	85	1.70	9.19	6.27	68
May 12	.22	200	96	0235	0315	.07	30	2.50	.17	.63	371
July 28	.65	587	599	0239	0355	.02	2	1.80	1.29	.01	1
Aug. 2	2.43	2,839	13,599	2141	2308	.90	391	2.30	15.78	4.28	27
1971											
May 6	.89	787	889	1010	1210	.11	13	1.64	1.60	.56	35
May 6	.25	198	71	1435	1545	.07	12	2.30	.13	.27	208
May 6	.27	225	94	1545	1710	.13	30	2.40	.17	.64	377
May 10	.43	350	200	0137	0347	.19	46	2.20	.36	.98	272
May 10	.19	180	72	1907	2004	.14	49	2.20	.13	.36	277
May 10	.64	639	716	2004	2053	.45	137	2.25	1.29	2.93	227
May 17	.58	609	719	2304	2400	.36	136	1.95	1.90	2.67	140
May 18	.36	320	198	0150	0227	.18	60	2.15	.52	.79	152
May 18	1.34	1,325	2,822	0227	0444	1.03	239	2.25	7.45	7.19	96
May 18	.31	222	75	1025	1147	.17	20	2.35	.20	.27	135
June 10	.18	171	65	0049	0135	.02	6	2.05	.17	.08	47
June 29	1.25	1,213	1,443	2148	2336	.12	26	1.50	3.81	.50	13

[1] Thiessen weighted. [2] Computed by the universal soil loss equation (*11*).

These comparisons illustrate that soil loss equations are not always reliable predictors of sediment yield because they make no provision for the attenuation of sediment in transport through the watershed. For example, the rainfall erosivity-cropping factor product (*RC*) of figure 3 would require an adjustment by C^4, the fourth power of the cover factor, to make the computed soil loss reflect the measured sediment yield. We can rationalize that a watershed "roughness" factor would be relatively low for row-crop fields in the May–June plow-plant season when the surface is bare. Therefore, we should expect low sediment delivery for 1969 and a relatively high value for 1971.

The 1970 rainfall amount (table 1) also was comparable to that in 1969 and 1971, but the rainfall erosivity was nearly double. Figures 2 and 3 show a moderately high erosivity during late April and early May 1970 and a very high erosivity in August, resulting from the most intense rainfall of record. The resultant 21-pct sediment delivery is between the values for the other 2 yr. This demonstrates the effect of the seasonal occurrence of storms on sediment delivery.

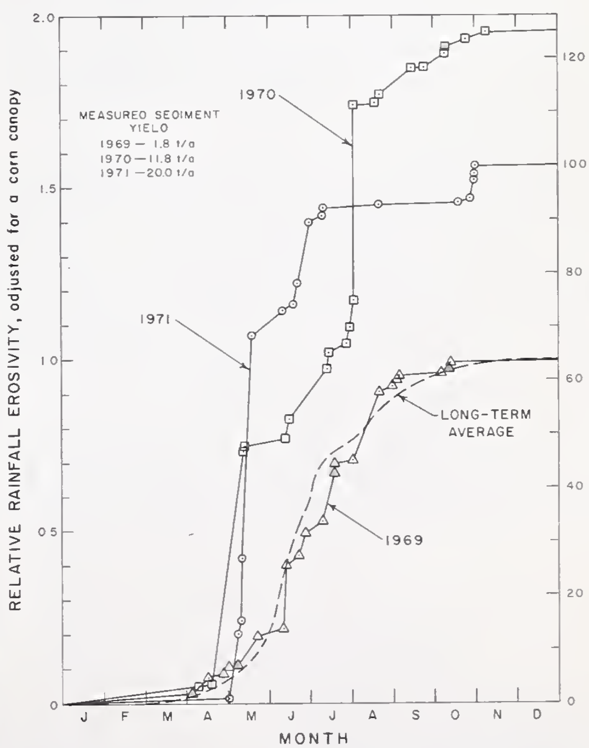

FIGURE 3.—Rainfall erosivity variation of figure 2, adjusted for crop stage.

Sediment-Delivery Interpretations—Storm Basis

Storm variations in gross sheet-rill erosion, sediment yield, and sediment delivery are shown in table 2 for one of the contour-planted, continuous-corn watersheds. Fifty-five of the best-sampled runoff events at watershed 1 in the 1965–71 period are listed. These represent a varied population, with measured sediment yields ranging up to 50 tons/acre for the event of June 20, 1967.

Computed sheet-rill erosion rates and measured downstream sediment yields (from sheet-rill erosion sources) at Treynor watershed 1 were compared (fig. 4). Only 33 pct of the variation in storm-sediment yield is explained by computed values of sheet-rill erosion.

To explain the scatter of figure 4, several hydrologic variables were examined for each storm event. The variables included rainfall amounts, rainfall kinetic energy (*KE*), kinetic energy × high 30-min rainfall intensity (*EI*), storm runoff volume, peak runoff rate, season, time, and moisture content in the top 6 inches of the soil profile. Season is the Julian date, and time is the number of days elapsed from January 1, 1965. When all sediment-associated variables were used in a stepwise multiple regression on each of the three dependent variables (sediment yield, erosion, and delivery), the results were as given in the table below.

Peak runoff rate and season explained much of the variability in sediment yield. Erosion rate was highly correlated with *EI*, which, of course, is a major variable of the universal soil loss equation for a given location. Sediment-delivery was most predictable on the basis of antecedent soil moisture content, season, and *EI*.

The appearance of seasonal and antecedent moisture variables that are correlated with sediment delivery is subject to several interpreta-

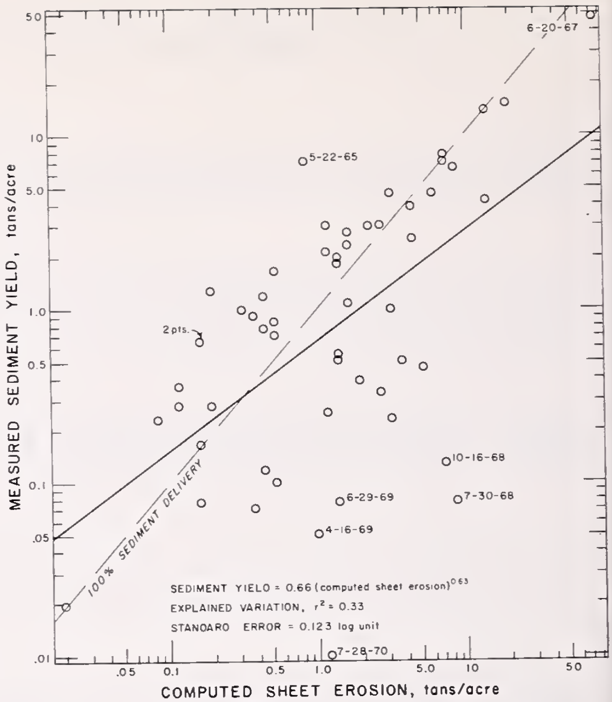

FIGURE 4.—Comparison of erosion rates and sediment yields from sheet-rill erosion sources for 52 well-sampled events on contour-corn watershed 1.

tions. For the 52 storms considered here, these two variables are relatively independent of each other; $r = -0.16$. Previous studies (*9*) showed high sediment-delivery percentages for storms occurring during the early crop stage. It was speculated that these were caused by rill development or soil moisture differences, or both, that were unaccounted for when the universal soil loss equation, based on plot studies, was applied to watersheds. However, this variation in sediment delivery may also be interpreted to be due to errors in estimating sheet-rill erosion (as Beer et al. conclude) or to the need for additional variables that can express the sediment conveyance characteristics of a watershed.

Dependent variable	Cumulative explained variation, R^2, due to addition of a given independent variable		
	1st	2d	3d
Sediment yield, tons/acre	Runoff peak (0.81)	Season (0.90)	*KE* (0.95)
Sheet-rill erosion, tons/acre	*EI* (0.96)	Season (0.97)	
Sediment delivery, pct	Soil moisture (0.36)	Season (0.62)	*EI* (0.83)

WATERSHED SEDIMENT-CONVEYANCE AND ROUGHNESS CONCEPTS

A watershed sediment-conveyance characteristic could be analogous to a hydraulic conveyance function for a channel, such as Manning's formula, in which $V \propto RS/n$. Moreover, watershed sediment conveyance could vary according to

$$D \propto RS/n \qquad (2)$$

where D=sediment delivery of equation 1 (an expression of the sediment conveyance properties of a watershed surface and drainage system),
R=an expression of flow geometry,
S=a watershed slope factor,
and n=a watershed roughness factor.

Such a function is in agreement with Maner's findings (*4*) that sediment-delivery percentage in the Red Hills physiographic region in Texas and Oklahoma varies with relief and maximum length of watershed. The latter variables are expressed as a ratio and are comparable to a slope factor. Roehl (*10*) used data from 15 Southeastern Piedmont watersheds to show that sediment-delivery ratios decreased with increasing watershed size and increased with an increase in watershed relief/length ratio. These relationships are all compatible with the concept of a watershed roughness or conveyance factor.

The foregoing watershed sediment-conveyance properties are based on differences between watersheds. When considering soil erosion and sediment movement on a single watershed, it is also possible to visualize different conveyance/roughness properties from season to season and from storm to storm. These properties would include differences in rilling, soil moisture levels, and overland flow obstructions.

The apparent sediment delivery from storms occurring in August and September on watershed 1, based on measured sediment yield and sheet-rill erosion calculated by soil loss equations, is nearly always less than 30 pct and is often 10 pct or less (table 2). We originally attributed this apparent low sediment delivery to the inadequacy of the soil loss equation to reflect seasonal erosion rates; that is, a higher erosion rate was thought to have been computed than actually occurred in August and September, and the resulting sediment-delivery percentage was too low. However, it is now proposed that the C-factor of the universal soil loss equation, which is 0.63 in the spring and decreases to 0.26 in the fall for these cornfields, is correctly gaging the effect of cover on soil loss rates. But it does not purport to represent a watershed roughness factor, which is needed to obtain the correct sediment-delivery ratio and thence the sediment yield.

The sediment-conveyance characteristics of a watershed vary from storm to storm in any given season. Figure 5 shows the percentage of sediment-delivery variation with sediment yield for 31 storms in June from 1965 through 1971 at watershed 1, for which any seasonal effect should be minimal. Some of this variation is due to differences in watershed roughness/conveyance properties such as rill formation, mechanical cultivation, and soil moisture changes. Preexisting rills on the watershed surface can convey eroded soil more efficiently than newly developed rills (*5*) because the hydraulic geometry is more favorable. We would expect the

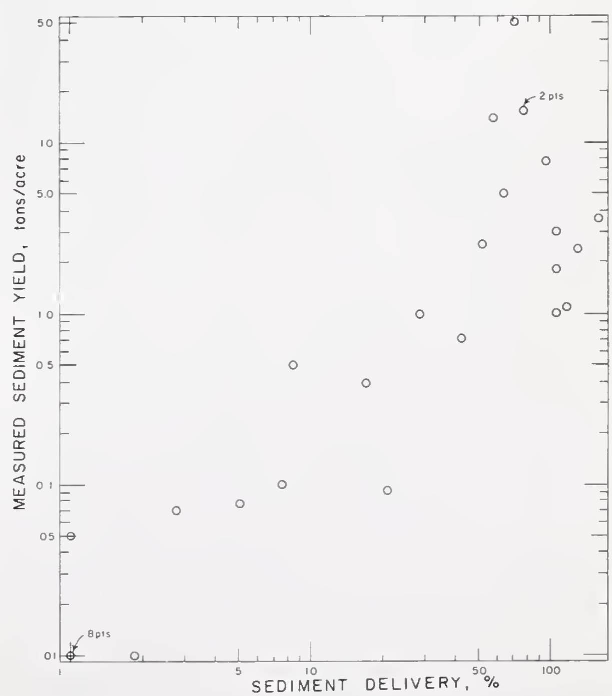

FIGURE 5.—Sediment-delivery variation with sediment yield for 31 June storms occurring from 1965–71 at contour-corn watershed 1.

R-factor in equation 2, which would be comparable to the hydraulic radius in the Manning formula, to increase with rill formation as compared with its value for sheet flow.

It is impossible at present to state the effect on sediment delivery of soil moisture and mechanical cultivation differences between these June storms, or the extent to which these two factors affect the relationship between actual and computed sheet-rill erosion rates on a watershed by the universal soil loss equation, or watershed conveyance properties even if soil losses are predicted accurately. We also suggest that there is an interaction between antecedent soil moisture content and storm rainfall intensities that cannot be typified by the 30-min maximum rainfall intensity used for calculating sheet-erosion rates. Wet soils are the principal reason that measured sediment yields can sometimes exceed calculated erosion rates. Antecedent soil moisture levels are correlated with sediment delivery, as shown in figure 6. Multiple correlation analyses of sediment delivery for the 31 June storms at watershed 1 show that peak runoff rate, runoff volume, and antecedent soil moisture explain 96 pct of the variation.

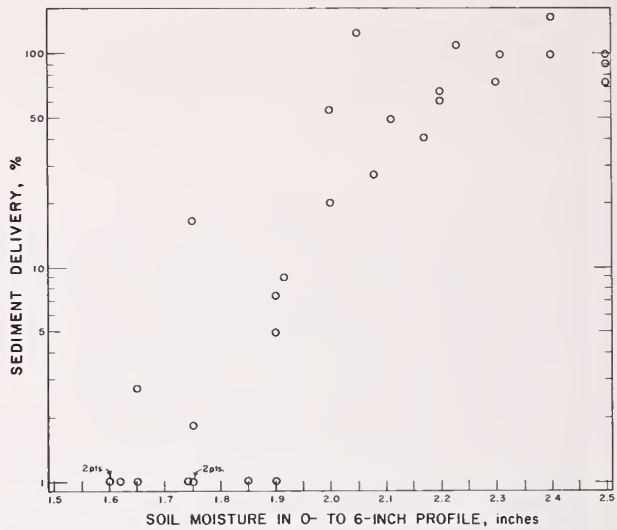

FIGURE 6.—Sediment-delivery variation with antecedent soil moisture level for 31 June storms on contour-corn watershed 1, 1965–71.

POTENTIAL FOR IMPROVING THE SEDIMENT-DELIVERY METHOD

Current agricultural and urban erosion problems can be better solved by a fuller understanding of watershed erosion rates and sediment yields. New insights into watershed sediment movement, on a storm basis, can refine the sediment-delivery method and improve its usefulness. These insights can also assist in the development of simulated watershed sediment models. The application of the foregoing analyses to modification of the sediment-delivery method to yield better estimates of sediment movement from loessial watersheds would include—

1. The best portrayal of the relationship between sediment yield and drainage area for the loessial region being considered. Piest (*8*) summarized research into the variation of sediment yield with size of drainage basin and found that the sediment yield decreased by about the negative one-eighth power of drainage area. The one-eighth power relation was a somewhat greater decrease in sediment yield with drainage area than Fleming obtained (as discussed in reference *8*) for 250 watersheds on four continents. The slope of the Fleming curve was probably low because it was based on a preponderance of sediment records from large areas and was not completely applicable to small watersheds. It can be reasoned that the sediment yield for minuscule areas approximates total sheet-rill erosion. In an example by Meyer (*5*), the percentage of total material transported declines rapidly with distance downslope until less than half of the total "point erosion" quantities are delivered to a location 160 ft downslope. Onstad (*7*) shows that net soil loss on a typical 9-pct, concave slope 75 ft long becomes zero at about 44 ft (the 100-pct sediment-delivery point) and that the sediment-delivery percentage to any point farther downslope declines rapidly. With these background data, the best-portrayed sediment yield-drainage area relation for the Treynor area should have a slope approximately as shown in the sediment-delivery curve of figure 7.

2. The sediment delivery-drainage area relationship dealing only with sheet-rill erosion. We propose to exclude other sediment sources and to add them later for individual watersheds whenever applicable. The sediment delivery-drainage area relation differs from the sediment yield-drainage area relation by a constant, $1/T$, since $D=Y/T$ (equation 1). The constant is based on the fact that sheet-rill erosion rates obtained by

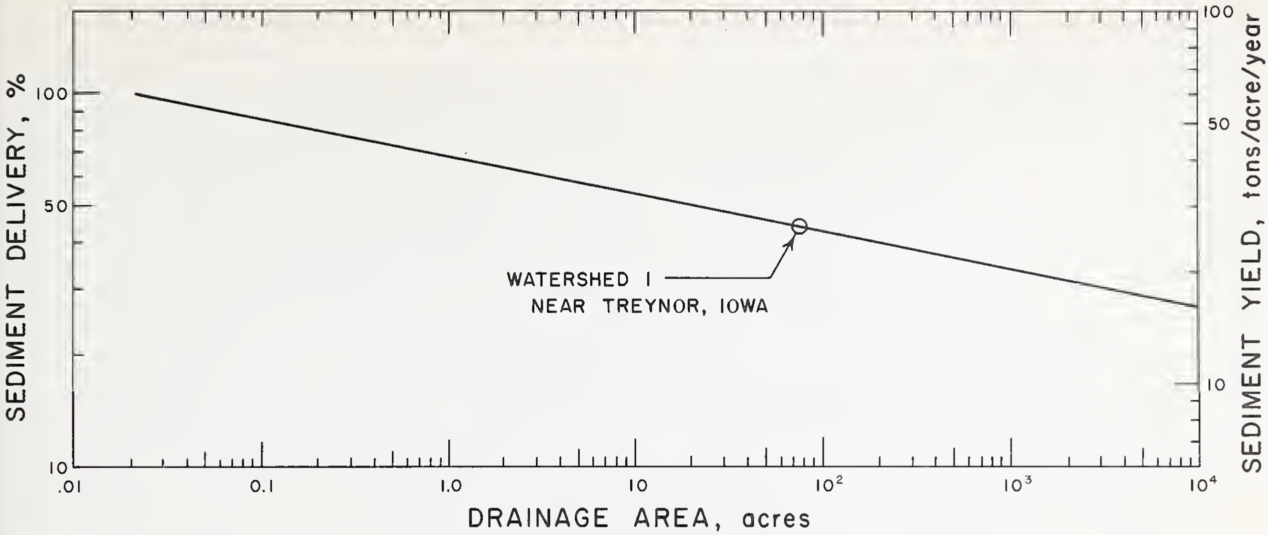

FIGURE 7.—Probable drainage-area relation to sediment yield and delivery, considering only sheet-rill erosion sources, from Iowa cornfields with an average 9-pct slope.

applying the universal or other soil-decline equations are not a function of watershed size in an assumed homogeneous region.

3. The assumption that the trend of the sediment delivery-drainage area relation is the same as previously demonstrated for sediment yield-drainage area. Others (*8*) have shown that sediment delivery decreases with approximately the one-eighth power of drainage area. However, Glymph's curve (fig. 1), as derived from Gottschalk and Brune's data for the Missouri River loess hills (*3*), was somewhat steeper than the others.

Applying these concepts to Treynor data, the 1965–71 average annual sediment yield from sheet-rill erosion sources for unterraced, corn-cropped watershed 1 was determined, from streamflow samples and measurements, to be 26.7 tons/acre/yr from 74.5 acres (table 1). The sediment delivery, computed by relating sediment yield to soil loss determined by the universal soil loss equation, was 46 pct (i.e., the sheet-rill erosion rate was 58.5 tons/acre/yr). A sediment-delivery curve with the ordinate in terms of both sediment-delivery percentage and sediment yield is shown in figure 7 for Treynor watershed 1. The constant k is evaluated as $100D/Y{=}1.72$. The sediment-delivery curve was drawn through the point representing watershed 1. Constraints in drawing the curve include the necessity for approaching 100-pct delivery on plot-size areas which form the statistical basis for the soil loss equations and for paralleling sediment yield-drainage area relationships.

The shape of the sediment-delivery curve for row-crop watersheds is apt to vary from that for pasture and small grains because the watershed surface roughness is much greater for the latter. Overland sediment movement on grass and small-grain watersheds must be attenuated more than on row crops; but, from the point where these sediments enter channels and are efficiently transported, sediment delivery should be the same. Therefore, in any given homogeneous region we would expect that, on the average, steep, cultivated watersheds that yielded the most storm runoff would have the highest sediment conveyance. As the effective surface roughness increases for watersheds with more gradual slopes, denser vegetation, or any other circumstances that would retard sediment movement, the sediment-delivery ratio versus area relation would decline more rapidly than for steep, row-crop land, to the point where the sediment enters an efficient drainageway. Then the relationship parallels the other curves. These concepts are illustrated in figure 8. In western Iowa, there is a wide variation in the size of watersheds draining into well-defined and efficient channels; the average is between 30 and 50 acres.

The divergence of the sediment-delivery curves of figure 8 does not seriously affect the accuracy of sediment predictions based on the sediment-delivery method. The preponderance of sediment

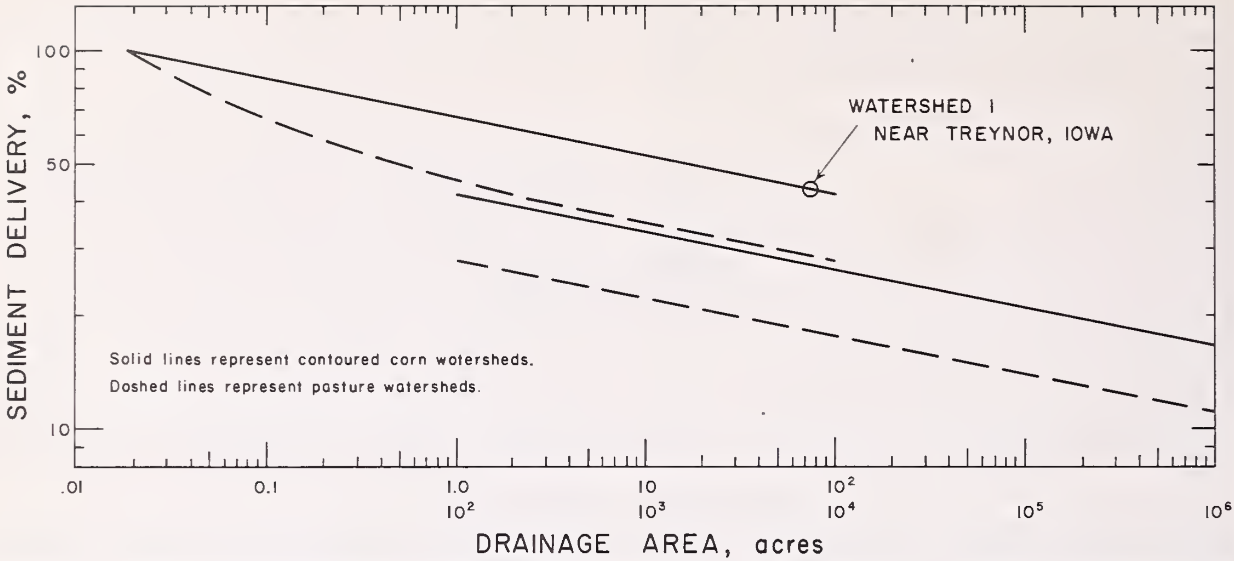

FIGURE 8.—Idealized sediment-delivery differences between row-crop and pasture watersheds in western Iowa.

produced by the sheet-rill erosion process will be from row-crop fields, and the use of a row-crop sediment-delivery ratio in mixed-cover watersheds will result in only a minor sediment-yield overestimate if not corrected. This statement is substantiated by table 3, where measured sediment yields for conservation watersheds 3 and 4 near Treynor are compared with sediment yields from contour-corn watersheds 1 and 2, 1965–1971.

Watershed 3 is a 107-acre bromegrass pasture. Watershed 4, 150 acres, is level-terraced and planted to continuous corn. Annual sediment yields from sheet erosion sources at watersheds 1 and 2 averaged more than 20 tons/acre; they were less than 1 ton/acre at watersheds 3 and 4. Gully erosion, which was not considered in the foregoing discussion, averaged 20 pct of the total for the 7-yr period.

TABLE 3.—*Average annual sediment yield, according to erosion source, from Treynor, Iowa, watersheds, 1965–71*

Watershed	Overland runoff (inches)	Sediment yield: Sheet erosion source (tons/acre)	Sediment yield: Gully erosion source (tons)	Sediment yield: Total (tons/acre)
W-1 (Contour corn)	4.80	26.7	501	33.4
W-2 (Contour corn)	4.45	20.9	389	25.5
W-3 (Bromegrass pasture)	1.75	.3	40	.6
W-4 (Level-terraced corn)	.67	.9	2	.9

SUMMARY

A 7-yr study of the four loessial watersheds in western Iowa shows much variability of sediment movement from field surfaces. Sediment yields for most years were profoundly influenced by one or two rainstorms, and the 1965–71 erosivity of rainfall was 180 pct of normal. These findings help to explain some of the variation noted in sediment-delivery ratios obtained by short-duration reservoir sedimentation and streamflow sampling studies.

Sediment yields from sheet-rill erosion sources averaged about 80 pct of the total sediment yield; erosion from gullies accounted for the remaining 20 pct. The annual sediment yields from sheet-rill erosion ranged from less than 1 ton/acre on conservation watersheds to 99 tons/acre for a

75-acre, continuous-corn watershed planted on approximate contour.

We suggest improvement in the much-used sediment-delivery technique as a needed step toward the development of a viable watershed sediment model and for better prediction of sediment movement on loessial watersheds. For example, although the present universal soil loss equation is an excellent base for a watershed sediment model, which would be improved by adding an antecedent soil-moisture factor, a more complete description of the rainfall erosivity and cropping factors would also be desirable. In conjunction with this modified soil loss equation, a group of terms must be introduced that will express the sediment conveyance/roughness characteristics of the watershed surface. The cropping factor of the universal equation, for example, may adequately express sheet-rill erosion rates from a small plot, but the efficiency with which these eroded sediments are transported across a watershed surface is unrelated to the erosion process and is presently not accounted for. Similarly, the relief, slope, slope length, surface-flow obstructions, watershed size, and drainage densities are all attributes that affect sediment conveyance on a watershed.

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A VOLUMETRIC ESTIMATE OF MAN-INDUCED SOIL EROSION ON THE SOUTHERN PIEDMONT PLATEAU

By Stanley W. Trimble[1]

(With an Appendix by David E. Penney)

INTRODUCTION

The southern Piedmont Plateau[2] is an outstanding example of man's disturbance of natural equilibrium: It is one of the most severely eroded agricultural areas in the Nation. Most of the Piedmont has been stripped of much of the topsoil, many areas have suffered erosion deep into the subsoil, and some areas have been gullied so badly as to render the land unsuitable for agriculture. The debris from this erosion has filled stream valleys and channels to varying degrees, often swamping the adjacent bottom lands. In areas of extremely severe erosion, streams may now be flowing 10 to 20 ft above their original beds, with bridges being literally buried (*7, 10–14, 17, 21–23, 25*).[3]

Although much attention has been given to the qualitative aspects of Piedmont soil erosion, there has been too little consideration of quantities. In their classic study of continental denudation, Dole and Stabler (*6*) concluded, from suspended stream loads at the fall zone, that the general area of the Piedmont was being denuded at rates from 0.8 to 1.3 inches/1,000 yr. (Measurements of suspended stream loads are themselves subject to considerable error.) Such low rates, reflecting in no way the extreme erosion taking place on the upland at that time, have been considered as the "lowering of the land" or as "regional erosion" (e.g., Menard, *19*). Later calculations of denudation of drainage basins have not differed greatly from those of Dole and Stabler (Judson and Ritter, *18*). Some researchers, however, have pointed out that figures previously cited as "the lowering of the land" are in fact only sediment yields and constitute only a small to very small portion of the gross or total erosion[4] from larger river basins (*8, 9, 16*). Holeman (*16*), for example, cites evidence indicating that annual sediment-delivery ratios might be as low as 5 pct from the Potomac River basin, which is partially within the Piedmont.

To realize that sediment-delivery ratios from the Piedmont have been relatively low, one need only consider the massive stream and valley sedimentation that has taken place within the Piedmont, especially in the headwater areas. Yet, little is known concerning the disparity between gross erosion and sediment yields from the Piedmont. Although sediment yields may be measured with a fair degree of reliability, the measurement of gross erosion is much more difficult.

PREVIOUS VOLUMETRIC STUDIES OF EROSION ON THE PIEDMONT

The late Carl B. Brown, sedimentologist with the Soil Conservation Service, made an attempt in 1940 to estimate the volume of total erosion from a large portion of the Georgia Piedmont. With a large-scale erosion survey of the upper Ocmulgee River watershed, an area of 1,414 mi^2, average depths of soil removal were assigned to each of the five general groupings of erosion

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[2] The southern Piedmont is that portion of the Appalachian upland having Piedmont soil, as defined in USDA soil surveys. The study area does not extend northward of the James River because of a significant change in soils.

[3] Italic numbers in parentheses refer to items in "Literature Cited" preceding the appendix to this paper.

[4] "Gross erosion" is the total amount of soil material dislocated and removed some distance by erosion within an area. "Sediment yield" is the amount of eroded material transported by a stream system to or past some point in the watershed. "Sediment-delivery ratio" is the ratio (at some locational point) of sediment yield to the gross erosion that has taken place upstream during the same period of time. All three of these measurements may be taken for any period of time.

classes (*20*, pp. 19–23). Such soil removal assignations were based on the average net thicknesses of material truncated from the profiles of the preexisting virgin soils. With these assignations, ranging from 2 to 36 inches, the average depth of total soil loss was calculated to have been almost 7 inches (*20*, pp. 19–23).[5] The same technique was used with only slight modification for two other Piedmont watersheds. The watershed of the Spartanburg, S.C., municipal reservoir was found to have lost an average of over 5 inches of soil (*1*), while the Lake Michie watershed near Durham, N.C., lost more than 4 inches (*2*).

The approach used by Brown for estimating total sediment production was innovative and useful.[6] Given the sediment yield from a large watershed (e.g., from Dole and Stabler[7]) estimates of sediment-delivery ratios and, conversely, upstream deposition could be obtained (*24*).[7] The estimates used by Brown, however, may be criticized because the assignations of soil removal depths were too generalized at the very large scale (1:15,840) for which data were available. Brown apparently accepted the published groupings of erosion classes, which were based more on qualitative than quantitative criteria. For example, the "very severe erosion" grouping (to which he assigned an average removal depth of 36 inches) includes several disparate erosion classes ranging from "very severe sheet erosion" to "very frequent or destructively large gullies" (*20*, pp. 9–10). At the very large scale of the data available to Brown, each erosion class should have been considered separately and assigned an average depth of soil removal based on the recommendations of the soil scientists performing the erosion surveys.

ESTIMATIONS OF EROSION FROM LARGE-SCALE SURVEYS

The approach of the present study is essentially that of Brown's except that the assignation of average depths of soil removal is more detailed. Areas of the Piedmont selected for evaluation of soil loss are those which have been surveyed and mapped at a large scale (1:20,000 or larger, mapped over aerial photo base maps), with erosion being a mapping criterion. The 34 large-scale surveys used in this study were of two general categories: (1) The USDA erosion surveys, "Erosion and Related Land Use Surveys," later called "Physical Land Surveys," which were completed between 1936 and 1941 at a scale of 1:15,840, with erosion considered as a main focus. For purposes of this study, soil removal depths were assigned by erosion classes, with each survey having from 15 to 35 such classes. (2) USDA soil surveys, most completed between 1949 and 1967, at a scale of 1:20,000. Soil removal assignations were made by mapping units (each mapping unit having an erosion classification), with each soil survey having from 25 to 150 mapping units.

The total area of the 34 surveys, excluding overlap is 15,126 mi^2, or 27.4 pct of the 55,049 mi^2 of the study area. The distribution of the survey areas is shown on map 1. It is believed that these surveys give a reasonably valid sampling of erosion conditions on the Piedmont, considering the relative physical homogeneity of the region.

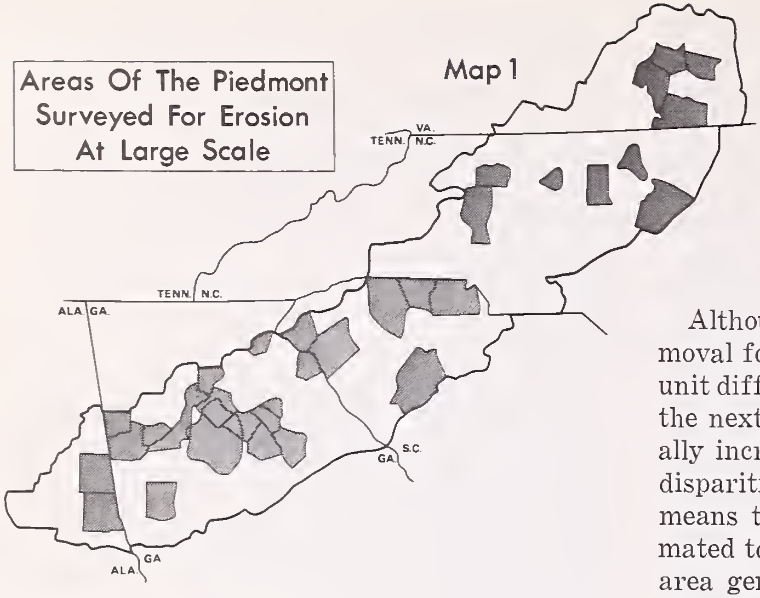
For both types of surveys, average soil removal estimates were assigned to each erosion class or mapping unit by experienced soil scientists who had actually taken part in the surveys themselves or who had considerable field experience in the general area of each survey. Although these assignations are estimates or value judgments, they are based on thousands of field measurements and observations[8] for each set of soil series, slope, texture, and erosion conditions,

[5] These average depths of soil loss were calculated by the present author by simply dividing the estimated volume of eroded material by the total area of the watershed subject to erosion. In the Lloyd Shoals watershed study, for example, the calculated soil loss was 467,200 acre-feet from 827,200 acres subject to erosion.

[6] I do not imply that Brown himself devised this technique for estimating erosion. Connaughton and Hough (*5*) utilized a similar technique as early as 1938. However, they gave no explanation of the technique, nor did they indicate the assumptions on which they proceeded (e.g., the average depth of soil removal for each erosion class). Only 64 pct of the study area had been surveyed for erosion.

[7] This assumes that available sediment-yield data are reasonably accurate. Moreover, one must extrapolate sediment yields for the entire period of European occupance, introducing additional error.

[8] Consideration was not given to soil regenerative processes operative during the period of European occupance. This is, the soil-forming processes may have slightly restored the qualities of a truncated profile over a period of a century. This was not considered to be a significant factor in most areas.



and therefore the values begin to assume the characteristics of statistical means.

For each survey, soil removal estimates were made by at least two soil scientists. Estimates for several surveys were made by three and even four soil scientists when qualified people were available. Each soil scientist worked independently in making his soil removal estimates. From each set of assignations for a survey, I calculated a total soil removal for the survey area. I then averaged the totals, giving a mean total volume removed from each survey area. This figure, divided by the total area surveyed, gave an average depth of soil removal from the survey area.[9] This process was repeated for all 34 large-scale surveys.

Although the assignations of average soil removal for a given erosion class or soil mapping unit differed somewhat from one soil scientist to the next and although these differences generally increased with the severity of erosion, the disparities tended to balance one another. This means that the total volumes of material estimated to have been removed for a given survey area generally differed little. For example, 24 of the 34 surveys have estimate disparities of less than 5 pct.[10] An excerpt from an evaluated soil survey is given in table 1.

By considering separately the assignations of each man, the total average depths of soil removed from Walton County were as follows: Robertson—6.704 inches, Bennett—6.759 inch-

[9] It will be noted that volume of eroded material is divided by the total area, rather than by the area of land subject to erosion. That is, areas of alluvial and colluvial deposition were not excluded. This was done in order to retain comparability in expanding the data to the entire Piedmont, wherein 1:500,000 maps were used. At the smaller scale, it was impossible to separate erosional and depositional surfaces.

[10] That the estimates were so similar should not come as a surprise. The soil scientists had occasionally worked with one another and had the same general perception. For example, their ideas concerning the virgin profiles of various soils were very similar.

TABLE 1.—*Excerpts from the Walton County, Ga., soil survey, with soil loss assignations*

Soil	Survey area (acres)	Percent of county	Estimated average depth of soil eroded (inches)[1]		
			A	B	C
Cecil coarse sandy loam, 2 to 6 pct slopes, eroded	16,995	8.0	4	5	5
Cecil sandy clay loam, 6 to 10 pct slopes, severely eroded	35,500	16.8	10	9	9
Madison sandy clay loam, 2 to 6 pct slopes, severely eroded	640	.3	9	9	8
Madison sandy clay loam, 10 to 15 pct slopes, severely eroded	730	.3	10	11	12

[1] Surveyed by Stanley M. Robertson (A), Jackson Bennett (B), and Paul H. Montgomery (C).

es, and Montgomery—6.764 inches. The average of the three depths, rounded to the nearest tenth, is 6.7 inches. Thus, the estimated total erosion from Walton County, Ga., would cover the county to a depth of 6.7 inches. Similarly computed figures of the other 33 survey areas ranged from 4.0 inches (Wake County, N.C.)[*] to 12.1 inches (Greene County, Ga.).

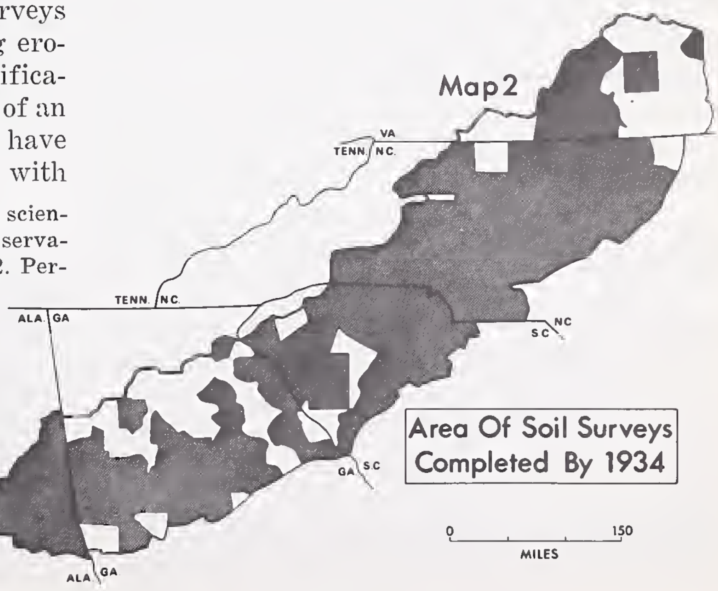
EXTRAPOLATION OF EROSION DATA TO THE SOUTHERN PIEDMONT WITH SMALL-SCALE SURVEY MAPS

Although I believed that the information obtained thus far might lead to some valid geographic generalizations of soil removal (e.g., soil loss was greater to the south), a more detailed spatial breakdown (e.g., by large watersheds or land-use regions) could not be obtained. Thus, a search was made for some suitable vehicle to expand the available data to the remainder of the study area. After a consideration of several possibilities, it was decided to use the 1:500,000 published maps of "Reconnaisance Erosion Survey" (RES) completed by the USDA Soil Erosion Service in 1934 (*27*).

At the national scale, the RES has been criticized especially for exaggeration. An evaluation by Held and Clawson, however, noted that "the results have stood up remarkably well" (*15*, p. 157; see also p. 63). For the Piedmont, a survey by this writer conducted among soil scientists familiar with the RES revealed attitudes toward the survey ranging from mild suspicion to strong acceptance. Among those questioned who had actually taken part in the survey, there was little doubt of its general validity at the scale originally mapped (1:62,500).[11] The surveyors pointed out that although the RES was conducted rapidly, most of the Piedmont soils had already been mapped before 1934 and that these soil surveys and maps were of great value in assessing erosion damage. For example, the texture classification "clay loam" was often an eroded phase of an original sandy loam, whereas a "clay" may have been a severely eroded phase (*4*, *17*). Thus, with a soil survey in hand, the surveyors had some general idea of erosion conditions before going to the field. Approximately 76 pct of the Piedmont had been surveyed for soils by 1934. The distribution of the surveyed areas is shown on map 2.

Another factor favoring the accuracy of the RES was that a considerable proportion of the fields were bare at the time of the survey, allowing the surveyors to use soil color as a rapid criterion. Also important was the dense road network existing at that time, giving the surveyors good access and mobility. The major limitation of the RES, rather than being the short time (2 months) allowed, was the lack of field experience among some of the younger soil scientists employed for the survey.

There is a chronological problem in using the RES to expand the data from the large-scale surveys (1:15,840 and 1:20,000) that were completed at a later date. This problem is not serious with the erosion surveys that were completed only 2 to 6 yr after the RES. The completion dates of the soil surveys were later, from 1949 to 1967, with a median date of 1958. For most of these areas, however, the soils had been surveyed



[11] Paul H. Montgomery, Rome, Ga., USDA soil scientist, 1931–65, and Dan Searcy, assistant State conservationist, Athens, Ga., USDA soil scientist, 1932–72. Personal communication.

starting in the late 1930's. The publication of the survey actually marks the completion of the survey. Still, there is some question as to how much erosion occurred between 1934 and the date of a survey.[12]

Another possible problem considered in using RES was the small scale (1: 500,000) of the published State maps. I suspected that the cartographic generalization at that scale might have negated some of the validity contained at the original mapping scale (1:62,500). By comparing the 1:500,000 maps with several of the original 1:62,500 survey maps (located in the National Archives, Washington, D.C., Record Group 221), I concluded that the reduction in scale and concommitant generalization did not appear to appreciably change the relative areas of each erosion class. An exception was the area of alluvial deposition along Piedmont streams. Most of these narrow valleys could not be shown at 1:500,000. Two soil scientists who were familiar with erosion over large areas reported that the published RES was as good a generalization of erosion as could be made.[13] I therefore decided to expand the large-scale data already obtained by using the 1:500,000 RES maps.

[12] The present writer has made a study (*26*) which indicates that erosive land use on the Piedmont was generally declining rapidly by 1934 and that the proportion of total erosive land use occurring after 1934 was relatively small for most counties. Based on this study, it is this writer's opinion that the amount of erosion occurring since 1934 as compared to the total amounts was relatively small for most areas and at a maximum would be no more than 10 to 15 pct of the total.

[13] Stanley M. Robertson, USDA soil scientist, 1939–72, and Jackson Bennett, USDA soil scientist, 1936–65, Athens, Ga. Personal communication.

Because of the relatively small scale, it was deemed appropriate to use only six general erosion categories for purposes of quantification.[14] These categories, which included RES erosion classes, are given in table 2.

The next step was to assign depths of soil removal to each of these six categories. That is, how much average soil loss is represented by little or no erosion (N), slight erosion (SL), etc.? Let N, SL, M, S, V, and G, then, be unknowns representing the average depth of soil removed for that category.

As the first step toward the calculation of these assignations (solving the unknowns), the 34 areas surveyed at large scale and for which quantitative information had already been obtained were delineated on the 1:500,000 RES maps. The area in each of the six erosion categories (as given in table 2) was measured with a polar planimeter. Thus, the RES shows Spartanburg County, S.C., as having 2 pct of its total area classified as little or no erosion (N), 11 pct as slight erosion (SL), 66 pct as moderate (M), 14 pct as severe (S), 2 pct as very severe (V), and 4 pct as destroyed by gullying (G). Using these proportions as coefficients for the six unknowns, we may write an equation for total soil loss for Spartanburg County with a total area of A:

[14] This was the recommendation of Paul H. Montgomery and Jackson Bennett. Erosion classes 17, 18, 28, and 3 (table 2) were of small areal extent. Since, moreover, these minor classes did not appear in most of the 34 sample areas, it would have been difficult to assign quantitative parameters to them. They were therefore included in other similar categories.

TABLE 2.—*General categories of soil erosion selected for quantification at 1:500,000*

General erosion category	Symbol	Erosion class from RES	Symbol
Little or none	*N*	Little or none	1
Slight	*SL*	Slight sheet erosion, occasional gullies	17
		Slight sheet erosion, frequent gullies	18
		Moderate sheet erosion	2
Moderate	*M*	Moderate sheet erosion, occasional gullies	27
		Moderate sheet erosion, frequent gullies	28
		Severe sheet erosion	3
Severe	*S*	Severe sheet erosion, occasional gullies	37
Very severe	*V*	Severe sheet erosion, frequent gullies	38
Destroyed by gullying	*G*	Destroyed by gullying	9

$$\text{Total soil loss} = 0.02N(A) + 0.11SL(A) + 0.66M(A) + 0.14S(A) + 0.024V(A) + 0.045G(A).$$

By dividing both sides of the equation by the total area (A), we obtain an equation for the average depth of total soil loss for the county:

$$\text{Average depth of total soil loss} = 0.02N + 0.11SL + 0.66M + 0.14S + 0.024V + 0.045G.$$

Recalling that from data at a much larger scale we have already obtained the average depth of soil loss for Spartanburg County, we may now write the complete equation:

$$0.02N + 0.11SL + 0.66M + 0.14S + 0.024V + 0.045G = 7.72 \text{ inches}.$$

Similar equations were written for the 33 remaining survey areas. A set of 34 equations with 6 unknowns is thereby obtained.

SOLVING FOR THE UNKNOWNS

Given exact quantities, any number of unknowns may be solved with the same number of equations. In the equations just devised, however, varying amounts of error have been introduced into both the right side of the equation and into the coefficients on the left side (errors in the survey, in the reduction of scale, and in map measurements). Thus, there are no exact single values for the unknowns. Rather, the values fall within some definite limits. Moreover, a "best fit" value for the set of unknowns will, when substituted in the equations, minimize error for purposes of prediction.

A unique statistical solution using a method related to least squares is offered for these "best fit" values (appendix). The solution is based, in large part, on estimated values for the unknowns furnished by soil scientists familiar with the survey.[15] These were

$N = 1$ inch $\qquad S = 9$ inches
$SL = 3$ inches $\qquad V = 18$ inches
$M = 6$ inches $\qquad G = 36$ inches

By using these values to set reasonable limits for the unknowns (appendix) the "best fit" values are (to the nearest hundredth)[16]

$N = 0.00 \qquad S = 7.36$
$SL = 4.16 \qquad V = 15.72$
$M = 5.90 \qquad G = 39.18$

Substituting these values into the 34 equations, we find that the predicted values are within 27 pct of the observed values (as computed from the large-scale surveys) about 65 pct of the time or within 54 pct of the observed values about 95 pct of the time (appendix).[17]

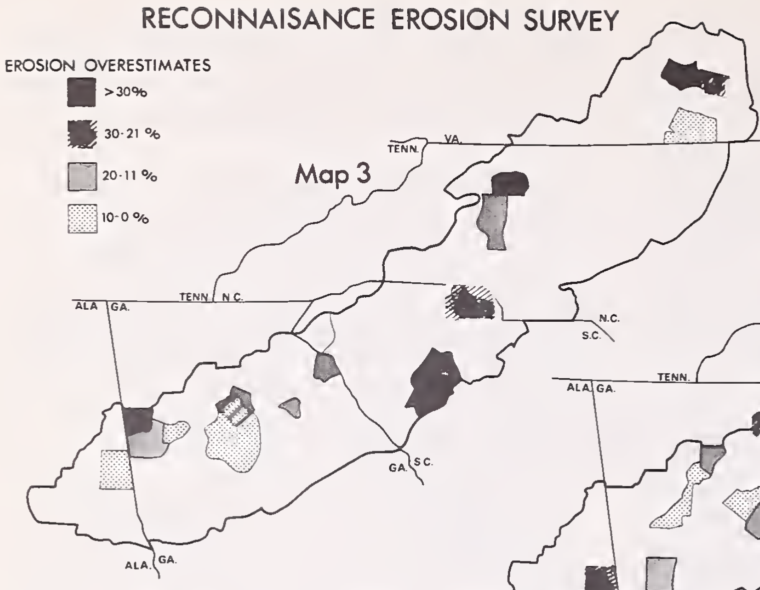
If the four obviously worst-fitting equations (table 3) are considered to be invalid (i.e., by assuming that the areas were poorly surveyed or that cartographic errors existed) and are deleted, the predicted values improve greatly. Then, the predicted values may be expected to be within 16 pct of the observed value about 65 pct of the time, within 33 pct about 95 pct of the time, and within 49 pct over 99.5 pct of the time. The prediction error for each survey area is presented in table 3.

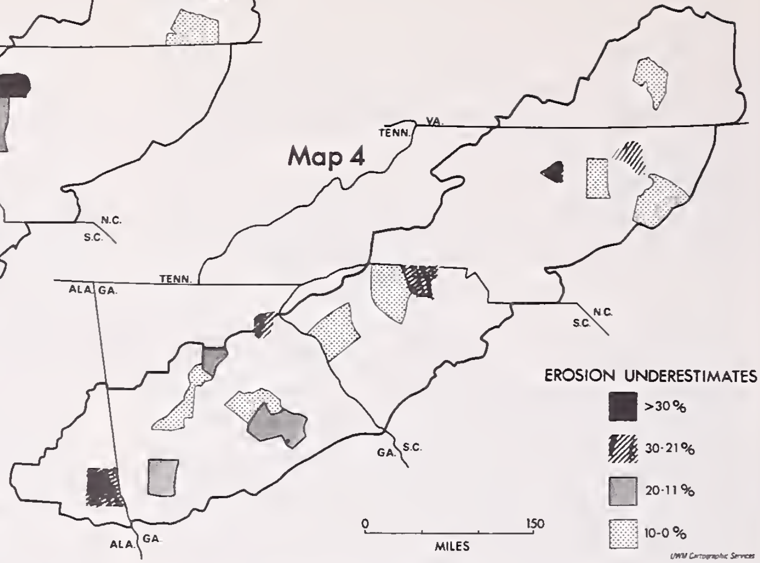
Note that the errors of prediction range from 29 pct underestimation to 77 pct overestimation. All but five survey areas, however, are predicted within 29 pct and all but three are within 39 pct. A spatial array of these errors (maps 3 and 4) reveals that positive and negative errors are widespread; neither is concentrated in one State or area. This indicates that the State surveys operated on a fairly comparable basis. Differences between individual surveyors or surveying teams possibly contributed the greatest portion of the error. One wonders, for example, if the extraordinarily large overestimates in Newberry and

[15] Jackson Bennett, Paul H. Montgomery, Stanley M. Robertson, and Dan Searcy. Personal communication.

[16] A problem introduced at this point is the fact that small areas of thin soils occur on the Piedmont (e.g., Goldston soils in the slate areas). For such thin soils, a given erosion category (e.g., severe erosion) would signify a lesser quantity removed than from adjacent deeper soils. Fortunately, the greater part of the Piedmont is covered by soils of rather similar depth characteristics, and the disparities can generally be ignored at the small working scale. Some error, however, will occur in those areas of shallow soil such as some portions of the "slate belt." (Jackson Bennett, personal communication.)

[17] It is to be noted again that the "observed values" are subject to various degrees of error.





Saluda Counties, S.C. (77 and 73 pct, respectively) are errors of surveying.[18]

Considering, then, the RES in conjunction with the values obtained for the six erosion categories as a good estimator of past erosion, I calculated the average depth of total soil erosion for the remainder of the Piedmont by county units. The values thus obtained ranged from 1.4 inches for Moore County, N.C., to 19.9 inches for Edgefield County, S.C.[19]

By plotting the values obtained from the large-scale surveys and the RES, I drew a map of soil removal (map 5). The most severe erosion was in South Carolina and the eastern half of the Georgia Piedmont, while the least erosion was in the outer (eastern) Piedmont of North Carolina. The average estimated depths of erosion by State are 6.8 inches from the Alabama Piedmont, 7.6 inches from Georgia, 9.6 inches from South Carolina, and 5.7 inches each from North Carolina and Virginia. The average for the entire Piedmont is 7.1 inches, with a standard deviation of 2.3 inches. In all, more than 6.1 *cubic miles* of soil are estimated to have been eroded from Piedmont slopes.

The erosion figures obtained in this study appear reasonable in light of the sparse existing data. For example, Happ (*11*) estimated that the Piedmont valleys of South Carolina were filled with modern erosional debris to an average depth of at least 4 ft. This is equivalent to an average soil removal from the upland of 3.8 inches.[20] To this must be added the average depth of material transported from the system as sediment yield, estimated to be 0.3 inch for the pe-

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[18] A number of soil scientists who took part in the RES suspected that erosion had been overestimated in Saluda, Newberry, and Edgefield Counties, S.C. (P. H. Montgomery, personal communication.)

[19] Only the Piedmont soils were tabulated. The very high figure for Edgefield County may be an extension of the overprediction for Saluda and Newberry Counties, which neighbor to the east. A soil survey of Edgefield County in 1935, while reporting much severe erosion, did not indicate the extent of devastation shown by the RES. (F. R. Lesh, W. J. Geib, A. E. Shearin, and C. H. Winsor, "Soil Survey of Edgefield County, South Carolina," USDA, Bureau of Soils, 1938). Fairfield County, directly east of Newberry County, was found to have lost 18.2 inches. This may be no exaggeration. A soil survey of this county in 1910 found 18.7 pct of the county to be so eroded and gullied that it was impossible to classify the soils. These areas were simply termed "rough gullied land." (M. E. Carr, G. A. Grabb, R. T. Allen, and W. C. Byers, "Soil Survey of Fairfield County, South Carolina," USDA, Bureau of Soils, *Field Operations*, 1911, p. 505.) The 1934 RES classified 36.1 pct of the county as "destroyed by gullying." It is possible that the proportion of this devastated land did, in fact, increase from 18.7 to 36.1 pct in the course of the 24 yr, considering the erosive land use taking place during those years. It is also possible, of course, that the RES exaggerated the area somewhat.

[20] Approximately 8 pct of the Piedmont is in bottom land and streams. The ratio of total area to bottom lands is therefore approximately 12.5 (100% ÷ 8%). By dividing the estimated average depth of modern sediment (48 inches) by total land/bottom land ratio, the average depth of eroded material is found to be 3.8 inches (48 inches ÷ 12.5 = 3.8 inches).

riod of European occupance.[21] Alluvium plus sediment yield gives an equivalent average soil loss of 4.1 inches. If one then assumes a 40-pct colluvium factor as reported in the Lloyd Shoals survey (*20*), the average total depth of soil erosion is estimated to be 6.9 inches. Although this is considerably less than the 9.6 inches estimated by this study to have been eroded from the South Carolina Piedmont, it does point up a relative similarity of magnitude, even when considered by two greatly disparate methods.[22]

[21] Based on data reported by Dole and Stabler (*6*), the average suspended-sediment yield from the South Carolina Piedmont was the equivalent of 1.23 inches of lowering per 1,000 yr. An increase of 25 pct is allowed for bedload giving a total of 1.54 inches/1,000 yr. Considering the South Carolina Piedmont to have been settled for 200 yr, or one-fifth a millenium at the time of Happ's study, the sediment yield was assumed to have been the equivalent of 0.3 inch of lowering ($1.54 \text{ inch} \times 1/5 = 0.3$).

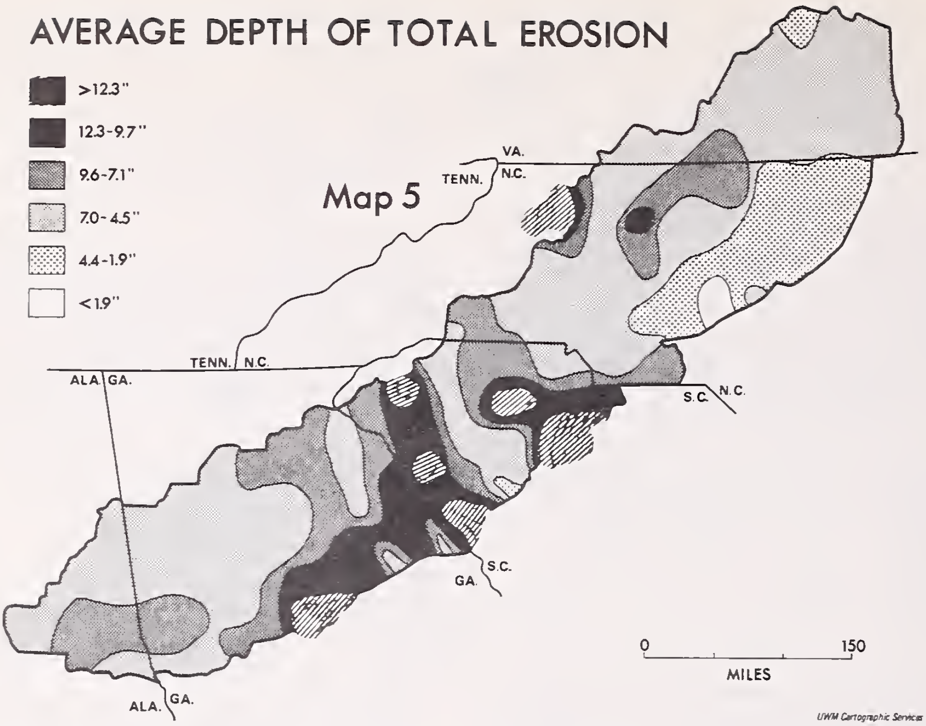
[22] Happ's estimate was a *minimum* average. That is, the average depth of alluvial fill may have been considerably more than 4 ft. (Stafford C. Happ, personal communication). Thus, the average depth of gross erosion as estimated from Happ's report may be somewhat greater and therefore more similar to the estimate reported by this study.

TABLE 3.—*Error resulting from the reconnaisance erosion survey to predict average depth of soil loss for 34 areas surveyed at large scale*

Name	Area[1] (mi²)	Depth of soil loss at large scale (inches)	Predicted depth of soil loss from RES (inches)	Error
Lloyd Shoals, Ga.[2]	1,414	6.70	6.86	+0.02
Wake County, N.C.	864	4.02	3.71	—.08
Spartanburg County, S.C.	832	7.72	7.52	—.03
Anderson County, S.C.[2]	772	10.16	9.31	—.08
York County, S.C.	697	8.76	6.50	—.26
Mecklenburg County, Va.	665	4.77	5.05	+.06
Newberry County, S.C.	628	5.35	9.45	+.77
Chambers County, Ala.	598	8.49	6.32	—.26
Iredell County, N.C.	594	7.02	8.08	+.15
Randolph County, Ala.	581	6.11	6.50	+.06
Fulton County, Ga.	523	6.90	6.62	—.06
Merriwether County, Ga.	499	7.34	6.02	—.18
Carroll County, Ga.	495	5.77	6.63	+.15
Charlotte County, Va.	468	6.09	5.66	—.07
Gwinnett County, Ga.	436	5.91	6.76	+.14
Alamance County, N.C.	434	6.04	5.54	—.08
Saluda County, S.C.	422	4.26	7.36	+.73
Greene County, Ga.[2]	414	12.08	9.96	—.18
Cherokee County, S.C.	394	8.76	6.50	—.26
Oconee County, S.C.	363	7.92	8.22	+.04
Morgan County, Ga.	357	8.34	7.25	—.13
Prince Edward County, Va.	354	6.15	8.57	+.39
Yadkin County, N.C.	335	5.41	8.51	+.57
Walton County, Ga.	330	6.74	6.53	—.03
Nottoway County, Va.	308	4.75	5.90	+.24
Haralson County, Ga.	285	5.00	6.70	+.34
Hart County, Ga.	257	7.31	8.37	+.15
Forsyth County, Ga.	243	8.21	6.76	—.14
Habersham County, Ga.	242	7.24	5.55	—.23
Douglas County, Ga.	201	6.01	6.64	+.10
Oconee County, Ga.	186	7.64	7.60	—.01
Lake Michie, N.C.[2]	168	5.55	3.98	—.28
Clarke County, Ga.[2]	124	7.60	8.87	+.17
Reedy Fork, N.C.[2]	73	7.76	5.52	—.29

[1] Area of Piedmont soils in each survey.

[2] USDA erosion surveys, completed 1936–40. The remainder are USDA soil surveys, completed 1949–67.



GENERAL SEDIMENT-DELIVERY RATIOS FROM THE PIEDMONT

This study did not attempt a detailed consideration of sediment-delivery ratios. However, some small-scale observations may be in order. If one considers the average duration of European settlement on the Piedmont to be approximately 200 yr and the average depth of soil eroded during that period of time as 7.1 inches, the total or gross denudation rate is 35.5 inches/1,000 yr. Assuming the sediment-yield figures from Dole and Stabler to be essentially correct and adding a 25-pct bedload factor (estimated), we find that the sediment yields of the Piedmont were 1.5 inches/1,000 yr.[23] Dividing the estimated sediment yields by the estimated rate of total erosion (35.5 inches/1,000 yr), the overall sediment-delivery ratio would be approximately 4 pct. This figure compares very well with the sediment-delivery rates for the Potomac River of approximately 5 pct cited by Holeman (*16*).

CONCLUSIONS

This study has estimated the total volume of material eroded from the Southern Piedmont during the period of European occupance. The figures obtained, while being much greater than the frequently cited denudation rates, do appear to be reasonable. Spatial differentiation is at large enough scale so that estimates of regional volumes or volumes by watersheds may be obtained. Finally, the erosion figures obtained in this study are considered to be only a first approximation and are subject to reevaluation when better data are available. Such data will come mainly from additional large-scale soil surveys.

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[23] The average sediment yield was calculated by adding a 25-pct bedload factor to the Dole and Stabler suspended-load rates for each major river and then weighting the rates by the relative areas of the watersheds. It will be noted that the figures of Dole and Stabler are used rather than more recent U.S. Geological Survey data. The reasons are twofold. First, despite the somewhat poor sampling of Dole and Stabler, their figures were obtained when erosive land use was relatively high. Second, present stream-load figures have limited utility for computing sediment-delivery rates. Many Piedmont streams are impounded into large reservoirs, both above and at the fall zone, with high trap efficiencies. Sediment yields obtaind downstream from the fall zone may be mainly measuring streambed erosion rather than upland denudation (*24*).

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I am deeply indebted to Professor David Penney for devising the ingenious statistical technique used in this study. Thanks also go to two of my colleagues, Professors Barbara Zakrzewska-Borowiecki and David H. Miller, Geography Department, University of Wisconsin, Milwaukee, for many helpful suggestions and criticisms of the text. Special appreciation is due Dr. Stafford C. Happ, USDA Sedimentation Laboratory, Oxford, Miss., for his many constructive criticisms and suggestions concerning my work. This paper profited immensely by his review. Likewise, I am grateful to Jackson Bennett, P. H. Montgomery, Stanley M. Robertson, and C. L. McIntire, veteran soil scientists, for their continued assistance. Appreciation is also due Don Temple and his staff at UWM Cartographic Services for the maps. I wish to thank my wife Alice, who spent hundreds of hours planimetering erosion maps and tabulating data. Finally I thank the Soil and Water Conservation Branch, Agricultural Research Service, USDA, for the research funds which made this study possible.

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APPENDIX

By David E. Penney[1]

Statement of the Problem

Let **A**, **X**, and **V** be, respectively, m by n, n by 1, and m by 1 matrices. All entries are real. If we write $\mathbf{A}=(a_{ij})$, $\mathbf{X}=(x_j)$, and $\mathbf{V}=(v_i)$, $1\leq i\leq m$, $1\leq j\leq n$, then the matrix equation

$$\mathbf{A}\cdot\mathbf{X}=\mathbf{V}$$

is equivalent to the m linear equations

$$\sum_{j=1}^{n} a_{ij}x_j=v_i\ (1\leq i\leq m).$$

If $m<n$, the solution (x_j) is in general nonunique (it may not exist); if $m=n$, there is in general a unique solution (although either existence or uniqueness may fail); if $m>n$, there is in general no solution (although there may be one or more).

In this appendix we are concerned with the last case, in which the system admits no solution. Indeed, in the particular problem under discussion, we are given the numbers a_{ij} and v_i (table A-1), together with i (as when we refer to the ith equation) and a weight w_i to be discussed later.

That the given system of 34 equations in 6 unknowns admits no solution is illustrated thus: The solution of the six-by-six system consisting of equations 4, 5, 9, 20, 30, and 33 is

$$x_1=-189.145258 \qquad x_4=-0.148596$$
$$x_2=206.103930 \qquad x_5=44.581977$$
$$x_3=13.711396 \qquad x_6=-479.493608$$

while if equation 4 is replaced by equation 25, the solution is

$$x_1=20.606238 \qquad x_4=9.745158$$
$$x_2=-13.465682 \qquad x_5=27.692459$$
$$x_3=4.205633 \qquad x_6=81.654260$$

TABLE A-1

i	w_i	a_{i1}	a_{i2}	a_{i3}	a_{i4}	a_{i5}	a_{i6}	v_i
1	73	0.0	0.44	0.25	0.3	0.0	0.0	7.76
2	124	.03	.0	.54	.13	.30	.0	8.35
3	168	.09	.80	.11	.0	.0	.0	5.55
4	414	.07	.0	.44	.06	.44	.0	12.08
5	772	.0	.23	.16	.49	.031	.085	10.16
6	1,414	.0	.01	.55	.40	.04	.0	6.70
7	186	.01	.0	.32	.59	.087	.0	7.64
8	330	.0	.0	.71	.27	.022	.0	6.74
9	357	.02	.0	.72	.16	.103	.005	8.34
10	436	.0	.0	.50	.47	.022	.0	5.91
11	243	.0	.0	.50	.48	.0	.02	8.21
12	285	.0	.04	.42	.55	.0	.0	5.00
13	495	.0	.0	.50	.50	.0	.0	5.77
14	499	.0	.07	.76	.17	.0	.0	7.34
15	257	.0	.04	.68	.04	.248	.0	7.31
16	201	.0	.0	.49	.51	.0	.0	6.01
17	242	.06	.0	.94	.0	.0	.0	7.24
18	697	.02	.11	.22	.59	.021	.044	6.65
19	394	.01	.01	.52	.46	.0	.0	8.76
20	832	.02	.11	.66	.14	.024	.045	7.72
21	363	.0	.13	.41	.24	.222	.0	7.92
22	628	.08	.09	.59	.09	.04	.11	5.35
23	422	.03	.33	.32	.25	.02	.05	4.26
24	335	.09	.32	.22	.0	.374	.0	5.41
25	594	.04	.17	.40	.21	.175	.0	7.02
26	434	.03	.17	.79	.0	.011	.0	6.04
27	864	.20	.58	.22	.0	.0	.0	4.02
28	468	.04	.0	.96	.0	.0	.0	6.09
29	354	.0	.0	.73	.0	.271	.0	6.15
30	665	.12	.08	.80	.0	.0	.0	4.77
31	308	.0	.0	1.00	.0	.0	.0	4.75
32	598	.0	.05	.65	.30	.004	.0	8.49
33	581	.0	.0	.59	.41	.0	.0	6.11
34	523	.0	.0	.51	.49	.0	.0	6.90

Under these circumstances it would seem advisable to search for a solution $\mathbf{X}=(x_j)$ that provides a "best fit" to all 34 equations. The method for doing so is called a least-squares method, and depends on finding a solution **X** to the problem of minimizing the function

$$E(\mathbf{X})=\sum_{i=1}^{m}\left\{\left[\left(\sum_{j=1}^{n} a_{ij}x_j\right)-v_i\right]\frac{w_i}{v_i}\right\}^2.$$

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This function arises from computation of the relative error in the ith equation,

$$\frac{\left(\sum_{j=1}^{n}\right) a_{ij}x_j - v_i}{v_i},$$

which is then multiplied by the weight w_i corresponding to that equation, the result squared, and the resulting numbers added for $1 \leq i \leq m$.

There are two reasonable questions at this point. First, why introduce the weights w_i? Second, why square the relative error—why not use the absolute value, or the fourth power?

To answer the first question, the numbers w_i can be set all equal to 1 if desired; but in the physical problem giving rise to these equations, the weights represent land areas over which measurements were made, and we felt it more appropriate to include them. Second, the error is squared because this is the natural generalization of an average—in the one-dimensional case, the average A of the numbers $b_1, b_2, b_3, \ldots, b_k$ is the number A which also minimizes the sum of the squares of the "errors" $b_i - A$.

In any case, we minimize the function E by setting all the partial derivatives of E with respect to its arguments $x_1, x_2, \ldots, x_n$ equal to zero, which leads to the n by n matrix equation

$$\mathbf{B} \cdot \mathbf{X} = \mathbf{U},$$

where $\mathbf{B} = (b_{ij})$ and $\mathbf{U} = (u_i)$ are given by

$$b_{ij} = \sum_{k=1}^{m} \frac{(w_k)^2 a_{kj} a_{ki}}{(v_k)^2}, \quad u_i = \sum_{k=1}^{m} \frac{(w_k)^2 a_{ki}}{v_k}.$$

When this technique is applied to the given system of equations, the least-squares solution $\mathbf{X} = (x_j)$ obtained is as given below. (The computations were carried out in single- or double-precision accuracy on the University of Georgia IBM 360/65 system computer, as were all subsequent computations.)

$x_1 = -7.929951$	$x_4 = 6.593614$
$x_2 = 7.182307$	$x_5 = 13.752226$
$x_3 = 6.434626$	$x_6 = 30.053024$

All would be well were it not for the fact that the actual answer represents inches of eroded soil, and the subscripts are so chosen that the values should get larger as the subscripts increase. Indeed, we have here a case where a relatively naive guess at the expected answer is far more likely to be correct than the numbers listed above; the best estimate for the solution is

$x_1 = 1.0$	$x_4 = 9.0$
$x_2 = 3.0$	$x_5 = 18.0$
$x_3 = 6.0$	$x_6 = 36.0$

The reason the least-squares solution differs so markedly from what must be nearly the correct solution is this: The values a_{ij} and v_i are themselves subject to considerable experimental error—this, too, is given in the initial problem. The problem is this: Given the initial data, the fact that these data are subject to an unknown error, and a reasonably good estimate of the actual solution, what indeed is the "most likely solution" in some sense yet to be made precise?

Analysis of the Difficulty

Given that the values of $\mathbf{A} = (a_{ij})$ and $\mathbf{V} = (v_i)$ are subject to unknown errors, probably not exceeding 20 pct in most cases, we ask if it is possible to make small changes δ_{ij} in the coefficients a_{ij} so as to make the "guess" $\mathbf{X} = (1,3,6,9,18,36)$ more nearly fit the 34 equations. More precisely, given $\mathbf{A} = (a_{ij})$ and $\mathbf{V} = (v_i)$ as above and given $\mathbf{X} = (1,3,6,9,18,36)$, do there exist numbers δ_{ij} so that

$$\sum_{j=1}^{n} (a_{ij} + \delta_{ij}) x_j = v_i,$$

$$\sum_{j=1}^{n} \delta_{ij} = 0,$$

and

$$\sum_{j=1}^{n} (\delta_{ij})^2$$

is minimized for $1 \leq i \leq m$? (Incidentally, the last condition turns out to be equivalent to the condition that the sum of the squares of all the $m \cdot n$ δ_{ij} is minimized.) There do exist such numbers, and they are easily found by the method of Lagrange multipliers. Note that the second condition above guarantees that the row sums of the matrix $\mathbf{A}$ will remain unchanged, a necessary condition derived from the original problem.

It turns out that the values of most of the δ_{ij} are in the vicinity of 0.01 or less. This means that small errors in the experimental data will cause large variations in the solution of the system of equations, and this without even altering the values of the vector $\mathbf{V} = (v_i)$. Nevertheless, the

values of such δ_{ij} are skewed unlike the expected errors in the experimental measurements, and there still remains the possibility of obtaining reasonably trustworthy estimates in spite of the presence of these unknown errors.

Solution of the Problem

We rely heavily on the fact that we have an initial estimate $\mathbf{X}_1=(1,3,6,9,18,36)$ of the solution. We proceed to generate a second estimate $\mathbf{X}_2$ in the following fashion. First calculate the relative errors in the right-hand side with $\mathbf{X}_1$. Divide these by 10. Reduce the weight (land area) of each equation by the corresponding percentage, but in no case by more than 50 pct. Find the weighted least-squares solution of the resulting system by the methods of the first section of this appendix. Average this with the first estimate, counting the first estimate 29 parts to the second estimate's one part. (There is no harm in erring on the side of conservatism here.) Adjust the result to lie within reasonable bounds:

$$
\begin{array}{ll}
0\leq x_1\leq 3.0 & 6.0\leq x_4\leq 16.0 \\
1.0\leq x_2\leq 6.0 & 10.0\leq x_5\leq 30.0 \\
3.0\leq x_3\leq 10.0 & 15.0\leq x_6\leq 60.0
\end{array}
$$

Call the new solution vector $\mathbf{X}_2$. Try this solution in the original system. In each equation, modify the coefficients on both sides by 1 pct of the amount necessary to produce a better fit. Keep the row sums of the modified coefficient matrix normalized to 1.0. Start over, thereby producing $\mathbf{X}_3$, $\mathbf{X}_4$, $\mathbf{X}_5$, and so on.

We iterated this process 5,000 times, but after the hundredth iteration the solution vector $\mathbf{X}_{100}$ was already quite close to the solution vector $\mathbf{X}_{5,000}$ at the 5,000th iteration. This suggests that the process is indeed convergent, and that a solution $\mathbf{X}_{5,000}$ has been found which is close to the least-squares solution of a system of equations obtained from the original system by minimal modifications. The solution estimates obtained at various stages of the iteration process are as follows:

	Number of iterations			
	100	1,000	2,000	5,000
x_1	0.000	0.000	0.001	0.004
x_2	4.150	4.163	4.162	4.157
x_3	5.935	5.906	5.905	5.903
x_4	7.399	7.359	7.358	7.357
x_5	15.784	15.725	15.723	15.719
x_6	38.871	39.196	39.193	39.183

We feel that the estimate in the last column is reasonably close to the actual solution.

Evaluation of the Results

We present a very elementary statistical analysis of the "value" of the solution $\mathbf{X}_{5,000}$ in the last column above. The above estimate was used to predict the right-hand sides of the equations and the resulting numbers compared with the actual right-hand sides. The percentage error was studied, first with all 34 equations used, and then with the worst fitting equations eliminated one at a time. The process was repeated with the initial estimate $\mathbf{X}_1=(1,3,6,9,18,36)$. The results are as follows:

Standard deviations, in percent

Number of equations used	Solution used	
	$\mathbf{X}_1$	$\mathbf{X}_{5,000}$
34	31.08	26.93
33	28.62	23.75
32	25.99	20.24
31	23.30	17.72
30	21.66	16.48
29	19.87	15.50

Thus, the estimate $\mathbf{X}_{5,000}$ is clearly a "better" predictor of the right-hand sides of the equation than $\mathbf{X}_1$. In addition, if one is willing to dispense with the four worst-fitting equations, $\mathbf{X}_{5,000}$ will predict the right-hand side with a standard deviation of 16.48 pct, so that the predicted value may be expected to be within 16 pct of the observed value about 65 pct of the time, within 33 pct about 95 pct of the time, and within 49 pct over 99.5 pct of the time.

STAGES OF DEVELOPMENT OF GULLIES IN THE WEST

By Burchard H. Heede[1]

THE PROBLEM

Mountain lands in the West, in general, receive less intensive use and management than agricultural croplands. Ephemeral gullies on these lands carry flows only at times of severe storm or spring snowmelt. They may develop in such major vegetation zones as desert, grass and brush lands, and open forests such as pinon-juniper and ponderosa pine types.

This discussion is based on research from the eastern and western flanks of the Colorado Rocky Mountains, as well as observations in New Mexico, Arizona, Nevada, and California. An attempt will be made to relate the development and morphology of ephemeral gully systems to stages of development. Present gully-classification systems do not yield sufficient information for the land manager who is confronted with problems of priorities in gully control, erosion rates, and sediment yields. Gullies not only develop from discontinuous channels, but probably change with time as part of general landscape evolution from youthful to old-age stages. As in landform development, these changes may cause substantial differences in erosion rates and sediment yields. Unfortunately, scarcity of data does not provide for the thorough understanding of gully processes that are basic to a definition of gully-development stages. Once we can describe gullies quantitatively in terms of stages of development, decisionmaking in land and water management will be substantially improved.

HISTORY

Gullies occur throughout the West in many different vegetation-soil complexes. But gullies are not often found on sites that support a healthy, dense vegetation cover, except where they invade from adjacent land. Gullies are rarely found in the well-forested subalpine region of eastern Colorado or in the oak brushlands of western Colorado. The ground surface of the latter is covered by humus, litter, and herbaceous vegetation such as Thurber fescue, and infiltration rates are nearly 5 times as high as for nearby sagebrush sites where gullies are abundant, according to data collected by the Rocky Mountain Forest and Range Experiment Station.

It appears to be fairly well established that many, if not most, of our present gully systems began their development or were reactivated in the last quarter of the last century, when population increases in the West led to an abrupt increase in grazing. Resulting depletion of the cover, coupled with droughts followed by abnormally frequent, large, high-intensity storms, trenched many valley floors. We also know that soil erosion, including gully formation, accelerated during the great drought of the 1930's, when an economic depression forced the population to rely heavily on the products of the land, with resulting overuse.

More recently, Loyd Barnett, of Forest Service Region 3 at Albuquerque, studied the development of a gully system on the Cibola National Forest near Magdalena, western New Mexico. Using aerial photographs and ground checks, he determined that the gully system on the Silverhill-Montosa watershed, 26.6 mi^2 in area, had 16 mi of gullies in 1936. In 1963, 27 yr later, the system had increased by 68 mi (425 pct). During the observation period, no new gullies formed. In contrast, aerial photographs indicated that during the same 27 yr, all gullies on the Monica watershed of the Cibola National Forest[2] (total length 7.6 mi) developed after 1936. These figures illustrate what we all know—gullying is still active on our watersheds.

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[2] Barnett, Loyd. 1965. Monica watershed condition survey, San Mateo Ranger District, Cibola National Forest. Open-file report, Region 3, Forest Service, U.S. Department of Agriculture, Albuquerque, N. Mex.

Gullies have been classified as continuous or discontinuous (*7*).[3] They are strikingly different in appearance. Continuous gullies begin their downstream course with many small rills, while discontinuous gullies start with an abrupt head cut. The headcut of the discontinuous gully may be located at any position on the slope of a hillside, while a continuous gully always starts high up on the mountainside and continues its course down to the main valley floor. The discontinuous gully may intersect the surface of the slope at any point, and thus be terminated.

After coalescence of many fingerlike rills, the continuous gully soon attains relatively great depth. It maintains approximately the same depth until the lowest reach above the gully mouth is approached, where depth decreases quickly along a concave profile that terminates at the gully mouth. A discontinuous gully rapidly decreases in depth downstream and thus develops a gully bottom gradient much gentler than that of the original valley floor. Where the gradients intersect, a sediment fan is built. There, a new gully may begin with a headcut. Discontinuous gullies (fig. 1) generally occur in series along the length of the drainageway (*2*).

Discontinuous gullies develop into continuous gullies. Although we did not observe the development of a continuous gully from a continuous channel, such a possibility cannot be dismissed. We all may have seen the formation of a continuous rill on a recent road-cut slope during a storm.

[3] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this paper.

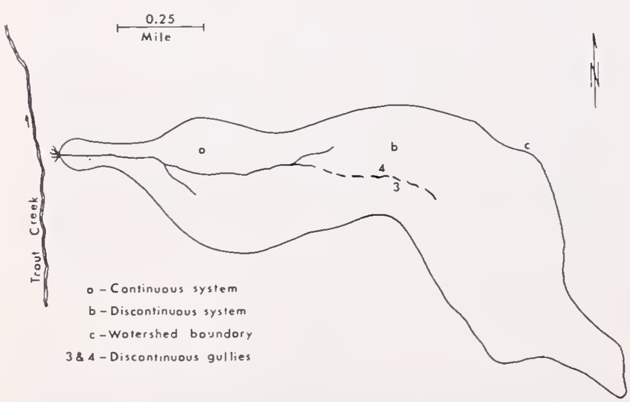

FIGURE 1.—The continuous and discontinuous systems of the Nursery Gully at Manitou Experimental Forest.

Yet at present, from our knowledge of processes, it is not clear when a rill becomes a gully.

The formation of discontinuous gullies is easier to comprehend than that of continuous gullies. Locally lowered resistance to erosion by grazing, trampling, fire, or other agents can lead to the formation of an initial furrow, scarplet, or small basin. Subsequent storms cause the head of the initial erosion feature to progress up-valley, while at its toe a small fan develops. As soon as a channel exists, a vertical headcut is formed. Concentration of water in the trench reduces channel storage and thus increases peak flows. These peaks are much larger than those of the former ungullied valley floor. Larger peak flows have greater velocities and cutting power, and the severity of the gullying processes is thus increased.

Several case histories document how discontinuous gullies fuse to form one large, continuous channel. For example, the Nursery gully system, on the Manitou Experimental Forest in the Colorado Front Range, still consists of both types of gullies. The headwater part of the system includes several discontinuous channels, located on the main drainage but separated by ungullied stretches and alluvial fans. A continuous channel system forms the downstream part of the Nursery gully. In its upper reach, coalescence is still visible, indicated by a rapid succession of pronounced channel nick points that, judged by gully depth and gradient development, represent fused discontinuous gullies. The nick points are 0.5 to 1.5 ft deep. Gully depth decreases from the first nick point to the lip of the second downstream, increases abruptly below the second nick point, and loses this increase rapidly again at the lip of the third nick point. This development is repeated several times until the channel depth reaches 4 to 5 ft, the average depth of the continuous system (*4*).

Two gullies of the discontinuous Nursery system were selected to test whether fusion of discontinuous gullies is part of the mechanics of gully-system development and to investigate the conditions that lead to gully fusion (*3*). At the beginning of the investigations, one gully was 286 ft long and had an average gradient of 0.07. A headcut (4 in fig. 2), 2.4 ft deep, marked the upper end of the gully; and alluvial fan terminated the gully on the undissected drainageway.

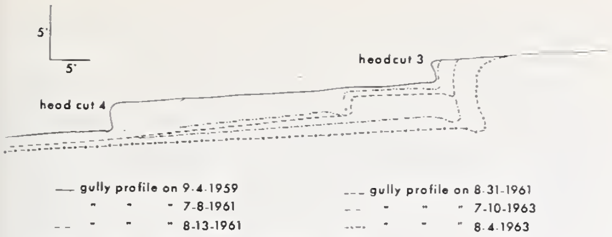

FIGURE 2.—The longitudinal gully profiles before and after the five flow-causing storms illustrate the development and fusion of headcuts 3 and 4.

Another discontinuous gully, 37 ft long, was located immediately upstream. It started with a 2-ft headcut (3 in fig. 2), had an average gradient of 0.06, and ended on the softly swaled drainage a few feet above the headcut of the lower channel. During 2 yr of a 7-yr observation period, the lower gully advanced its headcut by 42 ft, incorporating fully the smaller upstream gully (table 1). During this upstream progression, the headcut increased from an original depth of 2.4 ft to 6.3 ft, and the new fused channel attained a capacity more than twice the combined original gully capacities.

Upstream extension of discontinuous gullies does not always proceed by headcutting alone. Up-valley enlargement of discontinuous gullies can be accelerated by soil piping upstream from headcuts (*8*). These pipes may extend for a distance of several hundred feet into the ungullied alluvium. Collapse of the tunnels rapidly extends the gully.

Where soil pipes are caused by high-sodium soils and other factors, gully stabilization processes may be enhanced (*5*). On our Alkali Creek study area in western Colorado, pipes occurring in the gully banks extended not more than 30 ft from the brink of the gully. The piping-gully side slopes shear off repeatedly during rains and periods of heavy snowmelt, leaving nearly vertical walls. The soil masses are deposited on the opposite side slope, and force future gully flows against the piping bank. This leads to undercutting of the piping side slope, and results in more bank cleavage. With time, the thalweg migrates away from the deposition side slopes, and it appears that these slopes become stable. Growth of vegetation on the deposition slopes is favored by increased soil moisture. More water will infiltrate into the slopes because of the gentler gradient formed by the deposits.

The soluble salts, a large proportion of which are sodium, may also be leached more easily from the soils after mechanical disturbance. As sodium is leached from the soil (fig. 3), the pH will decrease and calcium will be more soluble and available for plant growth. While the leaching of sodium undoubtedly benefits the establishment of vegetation because the osmotic pressure in the soils decreases with salt concentration, calcium made available by the plants, in turn, will speed the leaching processes. Thus, gully side slopes stabilize rapidly, once plants become established.

The topography lining the Alkali Creek gullies, with its sodium-soil pipes, developed from young karstlike to a mature and old-age karstlike landform. According to Beede, as quoted by Thornbury (*10*), the stages of karst development

TABLE 1.—*Storms, flows, and erosion in the gullies below headcuts 3 and 4*

Storms						Inches of precipitation in periods prior to flow		Flow instantaneous peak[1]	Headcut progression upstream (ft)	
Date	Total (inches)	Duration (min)	Maximum intensities (inches/h)							
			5-min period	10-min period	15-min period	5 days	1 day	(ft^3/s)	No. 3	No. 4
July 7, 1961	1.07	28	4.80	3.60	2.88	0.50	0.08	16	0	7.5
Aug. 12, 1961	.39	38	3.84	1.92	1.28	.89	.22	...	.3	19.3
Aug. 30, 1961	.39	16	2.04	1.68	1.20	.23	.12	8	1.5	1.1
July 9, 1963	.87	50	3.36	2.82	2.20	.08	.08	...	...	11.1
Aug. 3, 1963	1.77	53	4.20	2.82	2.20	.19	.17	4	...	2.6
Total										41.6

[1] Although these figures were calculated to the nearest cubic foot per second, they should be regarded as approximations since certain simplifying assumptions were made. Flows in headcuts 3 and 4 were assumed to be the same because of the short distance between them.

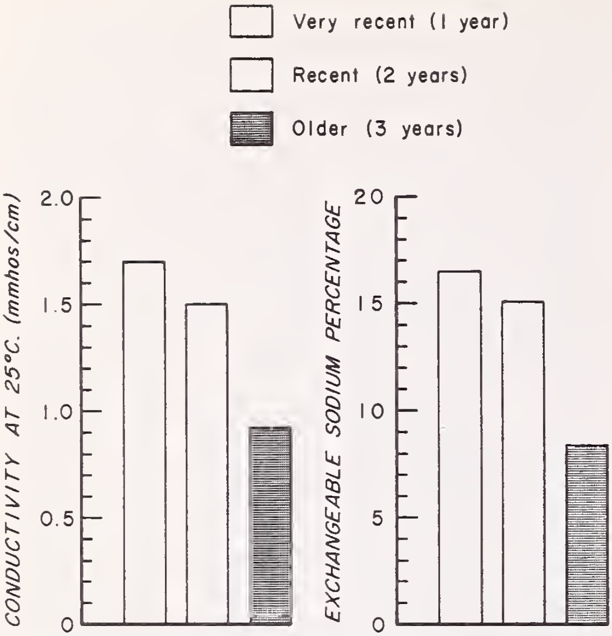

FIGURE 3.—Conductivity and exchangeable sodium percentage related to age of soil dump.

are characterized as follows: youth, the beginning of diversion of surface drainage to subterranean routes (development of soil pipes) ; maturity, well-developed underground drainage (pipes) with only major entrenched streams persisting as surface streams (gullies) ; and old age, the beginning of return to surface drainage (collapse of pipes).

In summary, the observed processes indicate that discontinuous gullies represent a youthful stage in gully development. Pronounced changes in channel width and bed slope as well as channel headward extension, leading to gully fusion, take place during the transformation to a continuous gully. No case history found in the literature shows that discontinuous gullies were not required for the development of a continuous gully.

The early stage of a continuous gully, characterized by the occurrence of nick points on the channel bottom, can be termed the early mature stage of development. Unless naturally controlled such as bedrock outcrops, the disappearance of nick points would indicate that a gully has attained its equilibrium slope. This in turn is an indicator that the gully is in dynamic equilibrium (*1*), also termed a stream at grade (*9*). Mature development would be an appropriate term for this type of gully. Our study areas support gullies approaching this stage, but the gullies could not be clearly defined as mature. The Nursery gully bottoms still exhibited some minor nick points, not controlled by bedrock, that possibly indicated the transition from the early mature to the mature stage of development.

MORPHOLOGY

If the postulate is correct that discontinuous and fused gullies represent youthful and early mature stages of development, respectively, a comparison betv ›en gully and river characteristics should show differences because, generally, rivers are in a mature or old-age stage of development. Their hydraulic geometry is characterized by a well-developed stream net, a concave longitudinal profile, and a shape factor representing stream competence. We investigated these parameters in 17 gullies located on Alkali Creek watershed, on the western flank of the Colorado Rocky Mountains (*4*). Horton's stream order analysis as modified by Strahler was applied (fig. 4). Since a large percentage of the watershed area was located uphill from the gully system, it could not be assigned to individual channels. If the large headwater area were related to the first-order streams, the resulting relationship between orders and respective areas would contrast sharply with general experience on rivers. Nearly 67 pct of the area of this fourth-order basin would be drained by first-order streams. In fourth-order river basins of various sizes in the United States, the average drainage area of first-order streams is about 1 pct (*8*). The Alkali gully system was still in the process of enlargement toward headwaters, as indicated by active headcuts at the upstream terminals of the individual branches. Thus the area drained by the first-order streams will decrease with time and stage of development.

Investigations of the longitudinal gully profiles showed that their concavity was too weak to be expressed by curvilinear equations; linear equations gave strong correlations. Although the problem of delineating trends in gullies is not basically one of statistics, because samples are not at random if derived from a given gully, the coefficient of determination (r^2) was used to test the validity of the linear relationships between thalweg elevation and thalweg length. All

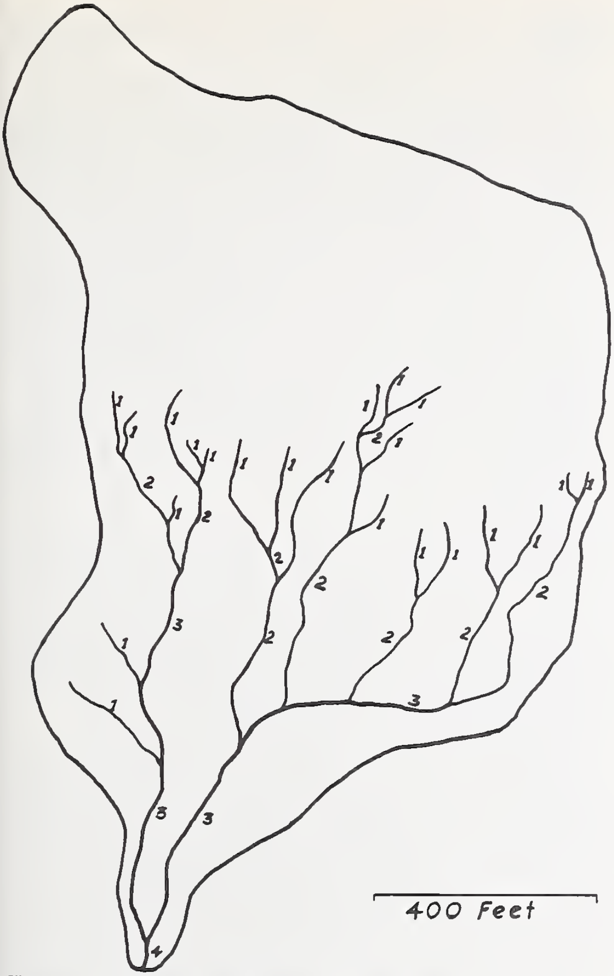

FIGURE 4.—The headwaters of the main gully on the Alkali Creek watershed demonstrate a youthful stage in the development of a drainage net of gullies.

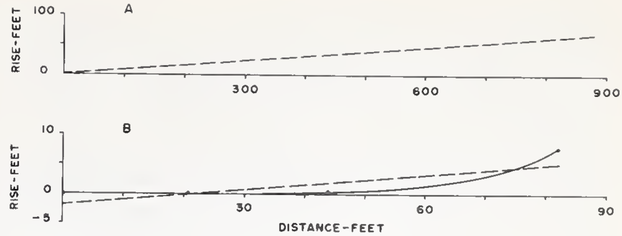

FIGURE 5.—Stream profile and regression line of gully 4 appear to be identical on the scale of graph *A*. Change in scale by a factor of 10 (graph *B*) shows that the stream profile is concave.

prediction equations for the gully profiles had extremely high r^2 values: from 0.92 to 1.00. Close examination of the resulting profiles revealed, however, that the lowest reach did not pass through the point of origin (fig. 5). At a distance of 0.3 to 11.7 pct of the total gully length (average 2.7 pct), the actual relations between elevation and distance were curvilinear. This conformed with the actual gully profiles, which were slightly concave in the lowest reach. In contrast, rivers show a pronounced concavity.

The shape factor, relating maximum to mean depth, expresses channel shape. This parameter must be interpreted cautiously, however, because it can relate to a variety of unusual gully cross sections. Mean depth is the cross-sectional area divided by the bank-full channel width. The shape factor of Alkali Creek research gullies was relatively high (average 2.0), representing a cross section with a large wetted perimeter that in turn indicates hydraulic inefficiency of the channels. Rivers in dynamic equilibrium have an average shape factor smaller than 2.0 (*6*) and thus a greater hydraulic efficiency.

Gullies and rivers exhibit great differences in stream net, profile, and shape factor. Since gullies are more recently formed than rivers, the tested hydraulic parameters of gullies express juvenile stages of development, which we termed youthful and early mature. The comparison of gullies with rivers suggests that gullies must mature before more stable conditions can be achieved. The ungullied headwater area of our study watershed will be gullied, therefore, before a mature, developed stream net is established. Greater hydraulic efficiency must be attained, represented by a change in the gully shape factor. This change will be achieved by increases in width and bed slope.

SEDIMENT PRODUCTION AND YIELD

It can be postulated that sediment production is usually highest in the youthful (discontinuous) stage of gullies. Discontinuous gullies have appreciable depth, but limited width, and a flat gradient. Immediately downstream from the plunge pool, located below the lip of the headcut, channel deposition occurs since more sediment is available than can be carried through the reach. Thus, in contrast to rivers, the gully can adjust its bed slope more rapidly than its width in response to changes in flow and sediment.

During the development of the discontinuous gully, lateral cutting, sloughing, and shearing off of vertical gully banks increase gully width, resulting in shallower cross sections for a given discharge. To transport the sediment at a given

discharge, necessary increases in velocity will be achieved by steepening of the bed slope, leading to gully extension and the formation of a continuous gully.

The possibilities for channel extension and gradient increase are more limited in continuous than in discontinuous gullies. Generally, they extend from headwater to the main valley floor, and have a gradient close to that of the original drainageway. It follows that, under given conditions, erosion rates are greatest during the transition stage from discontinuous to continuous gully, i.e., from the youthful to the early mature stage of development.

Rates of sediment production during an individual flow event depend not only on the stage of gully development, but also on the stability of the gully at the time of the flow. The importance of stability was investigated in a 7-yr study of the Nursery gully system, where five storms, during a span of 3 yr, fused two individual discontinuous gullies (*3*). Of these storms, only two had a magnitude larger than 1 inch (1.07 and 1.77 inches), and two were small, producing 0.39 inch each in 38 min and 16 min, respectively (table 1). The largest sediment producer, however, was the 0.39-inch storm of 16-min duration. It had the lowest intensity of all the storms, but produced the second highest peak flow. This largest sediment-producing storm (the third storm of the year) followed storms 8 weeks and 2 weeks earlier, which had left the gully in a raw, unstable condition, marked by overhanging banks.

It appears that, in ephemeral gullies, sediment loads are often more closely related to time and duration of flow than to magnitude of flow, the normal relationship for rivers (table 2). Thus, in main gully B, on April 15, a flow discharge of 79 ft^3/s carried a suspended sediment concentration of 63,855 p/m which represented a load of 316 lb/s. The next day, the flow increased to 107 ft^3/s, but had a concentration of 35,134 p/m and a load of only 235 lb/s. This behavior can be explained by the availability of sediment. If gullies experience a long period without flow, large quantities of sediment may be deposited in the channel by bank sloughing and similar processes. When the first flow occurs after such a period, much sediment is readily available for transport. As the flow continues, sediment becomes less easily available and the load decreases, sometimes so drastically that the flow eventually appears clear to the casual observer.

The examples illustrate the difficulties in predicting sediment production and yield for early stages of gully development. It can be postulated that, once a gully achieves the mature stage—dynamic equilibrium—prediction equations will be meaningful, unless a new set of conditions, brought about by climatic, orographic, land use, or other changes, requires adjustment of the streambed. This, of course, is true also for rivers.

TABLE 2.—*Suspended-sediment samples from ephemeral gully flows on Alkali Creek watershed, Colorado Rocky Mountains, in 1964. The flows caused by snowmelt were preceded by a dry-channel period of 1 yr.*

Sampling station	Watershed area (mi^2)	Date	Flow: Average velocity (ft/s)	Flow: Discharge rate (ft^3/s)	Sediment: Concentration (p/m)	Sediment: Discharge (lb/s)	Composition (pct): Sand	Composition (pct): Silt	Composition (pct): Clay
Gully 3	0.2	Apr. 16	2.4	7.1	35,706	15.8	12.9	53.4	33.7
Do	.2	Apr. 29	1.8	.6	12,402	.5	7.5	54.6	37.9
Main gully A	1.1	Apr. 14	1.1	8.2	20,766	10.6	1.5	57.9	40.6
Do	1.1	Apr. 16	1.3	19.5	13,432	16.3	2.5	62.3	35.2
Do	1.1	Apr. 28	1.8	6.6	4,499	1.9	5.9	63.5	30.6
Do	1.1	May 26	1.1	.6	19	.0007	....	....	....
Main gully B	10.4	Apr. 15	4.9	79.4	63,855	316.4	34.1	45.1	20.8
Do	10.4	Apr. 16	6.5	107.2	35,134	235.0	51.4	24.9	23.7
Do	10.4	Apr. 29	3.3	35.1	4,628	10.1	17.3	73.8	8.9
Do	10.4	May 26	1.4	1.1	12	.0008	....	....	....

CONCLUSION

Gully development should be recognized in terms of landform evolution, proceeding from youthful to old-age stages. In this study, youthful and early mature stages of gully development were defined; development to the early mature stage coincides with the transformation of discontinuous into continuous gullies. Comparison of hydraulic geometry of gullies with that of rivers suggests that the mature stage should be characterized by dynamic equilibrium. Although this stage was approached by some study gullies, its existence could not be verified. Gully development is not controlled by waterflow alone, however. In ephemeral gullies, vegetation grown during dry channel periods can exert major influences. Criteria for the mature gully stage may, therefore, not be given by stream equilibrium alone, but may include other aspects of stability such as channel vegetation.

Because insufficient data are available on stages of gully development, gullies cannot be quantified in terms of gully mechanics and morphology. Watershed managers would have a useful tool if gully stages could be expressed in terms of erosion rates and sediment yields.

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MECHANISMS OF EROSION AND SEDIMENT MOVEMENT FROM GULLIES[1]

By R. F. Piest, J. M. Bradford, and R. G. Spomer[2]

INTRODUCTION

Gully erosion occurs in most locations where an erodible soil mantle is exposed to concentrated runoff from rainfall, melting snow, or both. The identifying characteristic of an active gully is an erosional scarp, usually steep-sided and several feet high. Gullies can form continuous or intermittent channels. In the Central States they may occur on the perimeter of upland fields and actively advance into the fields. Many of the gullies in northern Mississippi lack drainage areas above the gully scarp, but are eroded by rainfall, runoff, and associated weathering forces occurring on the gully itself. By contrast, valley head gullies (sometimes called valley trenches) of the Great Plains and arid regions of the Western United States are often located on ephemeral streams that drain large areas.

Peterson[3] and other early researchers discussed causes for the formation of gullies in valleys of the Central and Western United States. The term "accelerated erosion" was used because land use (misuse) caused by tilling, livestock grazing, roadbuilding, and other activities of man was widely believed to be an important factor affecting gully erosion rates. The cyclic theory of gullying was also widely accepted. Geologists have noted at many locations that some present-day gullies are eroding in drainageways that were previously eroded and filled because of climatic changes or other disturbances to the hydraulic regime in the geologic past. Although both explanations are plausible, perhaps the only benefits from studies showing the historical and geologic progressions of gullies would be estimates of changes in runoff regime and gully hydraulic geometry associated with channel metamorphosis.

Mechanisms affecting gully erosion in one region may not be similarly operative in another region. Studies at the North Central Watershed Research Center primarily concern valley head gullies draining field-size areas in the Missouri Valley deep loess region. In this report, we discuss the sediment movement from four of these gullies and explore the mechanisms that seem to affect gully erosion rates.

THE STUDY AREA

The depth of the erodible loess mantle overlying glacial till in the Missouri Valley decreases with distance from the river. In the Agricultural Research Service study area near Treynor, Iowa, the loess cap is more than 80 ft thick on ridges and thins to about 15 ft in the valleys. In this rolling countryside, land slopes vary from less than 4 pct along ridges and valleys to about 15 pct on hillsides. Deep gullies in the valleys are generally incised to, or slightly into, the till. Because the loess soil has a moderate percolation rate and the underlying till is relatively impermeable, a saturated zone occurs above the loess-till interface and causes seepage from channel banks. The effect of this seepage on gully stability has been the subject of much conjecture. The four study watersheds and outlet drainageways are described in table 1.

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TABLE 1.—*Watersheds and outlet gullies near Treynor, Iowa*

Watershed				Outlet drainageway			
				Scarp			
No.	Size (acres)	Crop	Treatment	Condition	Distance to measuring weir (ft) 1965	Distance to measuring weir (ft) 1972	Gully bank condition
1	74.5	Corn	Field contoured.	Advancing and raw.	260	420	Eroding.
2	82.8	Corn	Field contoured.	Nonadvancing, raw, and chutelike.	690	700	Eroding.
3	107	Bromegrass	Rotation grazed.	Stepped	700	700	Mostly stable.
4	150	Corn	Level terraced.	Stepped	850	850	Stable.

INSTRUMENTATION AND MEASUREMENTS

Gully erosion rates are measured by several procedures. Planimetric mapping from low-altitude aerial photos gives sufficient detail of linear advance rate and areal change. Volumetric gully erosion rates have been determined by traditional cross-sectioning methods and by photogrammetric procedures.[4] In recent years, targeted, low-altitude photos of the eroding channels have been made annually. However, special efforts have been made to define gully sediment movement at all times during storm runoff; this is accomplished by the dual sampling of streamflow at channel cross sections above and below the gully headcut. Nearly all samples were collected (at 1- to 3-min intervals during rising water stages and less frequently during the recession) with a U.S. DH–48 hand sampler by the equal transit rate (ETR) method. Streamflow samples collected near the runoff-measuring weir located below each gully headcut, or scarp, represent sediment eroded from both the field and the gully, whereas samples collected above the gully headcut should reflect the quantities of sediment contributed by sheet-rill erosion. The difference between these sediment concentrations and erosion rates is a consequence of erosion originating from both the gully headcut and the channel banks between the headcut and the downstream weir. (In some instances, as illustrated in figure 1, sediment from sheet-erosion sources above the gully headcut actually exceeded total erosion downstream and resulted in a net deposition of sediment in the gully. This circumstance was a common occurrence on conservation watershed 4 (150 acres), where sediment produced from 12 acres below the level terrace system was deposited and held in the channel by vegetative growth.)

Additional measurements utilized in this gully study include rainfall and runoff amounts and intensities, soil moisture content, ground-water levels, and various physical and hydraulic attributes of the watersheds and drainage systems.

DATA AND INTERPRETATIONS FROM FIELD STUDY

Gully erosion measurements began in 1964 at Treynor watersheds 1 and 2 and a year later at conservation watersheds 3 and 4. Table 2 summarizes sediment yield from both the upland field and the gullied drainageway for all four watersheds, 1965–71. Overall, about one-fifth of the total sediment yield resulted from gully erosion.

Gully-erosion rates from conservation watersheds 3 and 4 were typically of minor importance. (The most significant gully erosion on a conservation area occurred June 20, 1967, on bromegrass pasture watershed 3, where an intense 3.9-inch rainfall on the saturated soil surface caused 2.0 inches of runoff and a loss of 120

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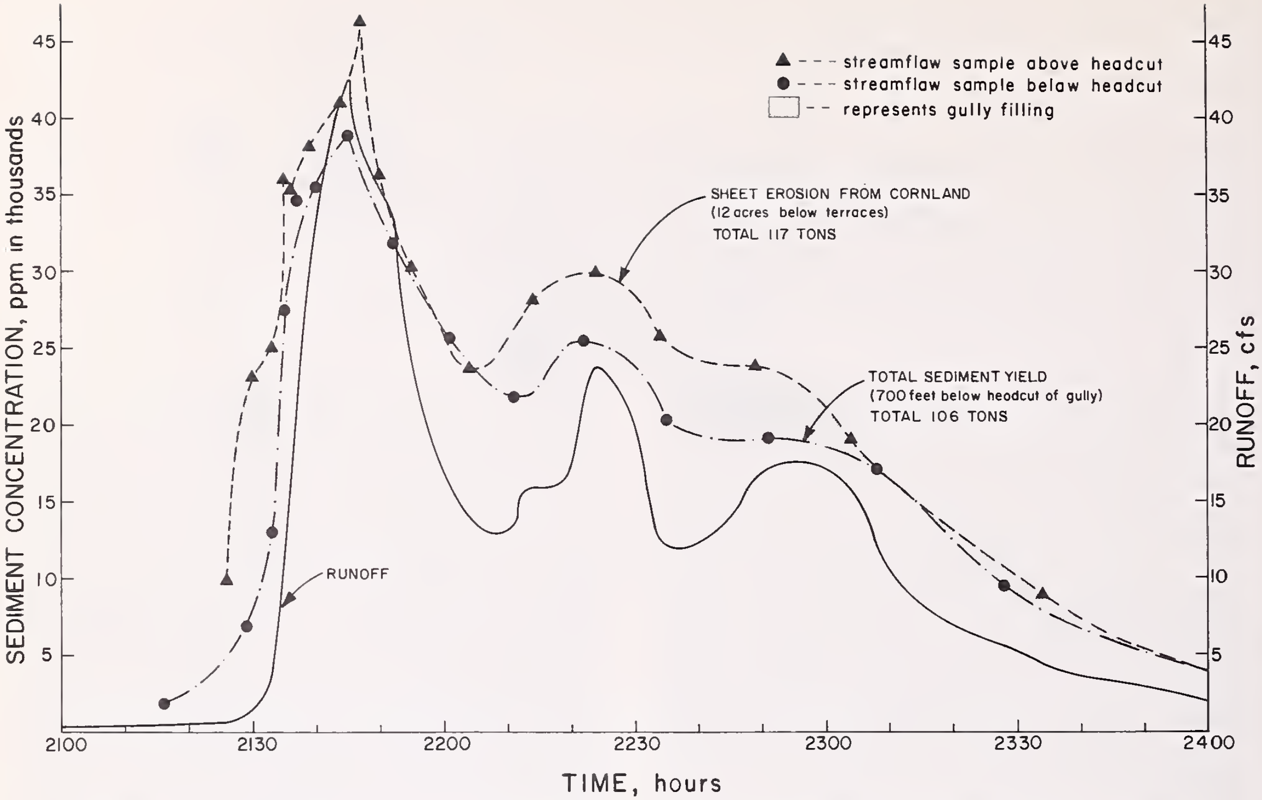

FIGURE 1.—Gully filling due to intense storm on unprotected upland field, watershed 4, June 20, 1967.

tons of soil from the gully.) Table 2 also shows that surface runoff and gully-erosion rates were much higher for contour-corn watersheds 1 and 2. These two channels are actively eroding—watershed 1 gully mainly by headcut advance and watershed 2 by lateral erosion of gully banks.

Figure 2 shows an aerial view of the channel system and a closeup of the gully headcut at watershed 1. The areal growth of this gully from 1965 through 1971 is portrayed in figure 3 by survey period; surface runoff and gully-erosion rates for these periods are also tabulated. Gully-erosion rates at watershed 2 were nearly as great as those at watershed 1, even though little material was removed from the vicinity of the headcut; the major sediment source was the eroding gully bank in the 700-ft channel reach between the headcut and the runoff-measuring weir.

Interpretations Based on a Few Selected Storm Events

Figure 4 shows gully-erosion rates at watershed 2 during the record rainstorm of June 20, 1967. These rates were computed from 20 streamflow samples collected above the gully headcut, 17 streamflow samples collected at the downstream cross section, and known runoff rates provided by continuous water stage records and a calibrated weir stage-discharge relationship. During this storm, 690 tons of soil was eroded from the gully. The gully-erosion rate during the most erosive period of the storm was 50 tons/min.

An examination of gully-sediment concentrations and discharges during the course of runoff events showed that at least two general conditions are necessary to cause gullying.[5] Soil debris must exist and runoff must be sufficient to entrain and transport this debris. In the preceding sections, we have dealt with the total gully-erosion process in a general manner; however, in a closer examination of the mechanics of gully erosion, it is necessary to distinguish between the two subprocesses of debris cleanout and renewed debris production. It is sometimes impossible to separate the effects of important variables on

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TABLE 2.—*Sediment yield by erosion source from Treynor, Iowa, watersheds, 1965–71*

Year	Watershed	Annual precip. (inches)	Runoff (inches) Ground water	Runoff (inches) Surface	Runoff (inches) Total	Sediment yield Sheet-rill (tons/acre)	Sediment yield Gully (tons)	Sediment yield Total (tons/acre)
1965	1	45.35	3.56	10.62	14.18	44.1	1,154	59.6
	2	44.34	2.97	10.68	13.65	36.5	656	44.4
	3	44.28	4.62	4.60	9.22	[1].4	[1]86	1.2
	4	44.87	10.56	2.51	13.07	[1].9	[1]16	1.0
1966	1	20.32	2.54	.65	3.19	6.7	93	7.9
	2	20.53	2.40	.88	3.28	8.6	177	10.7
	3	22.01	2.54	.38	2.92	[1].1	[1]10	.2
	4	21.88	5.91	.19	6.10	.6	14	.7
1967	1	38.25	2.27	11.57	13.84	99.0	1,455	118.6
	2	37.61	2.50	10.45	12.95	75.2	1,374	91.8
	3	34.23	3.30	2.65	5.95	.6	120	1.7
	4	34.55	7.28	.73	8.01	2.9	[2]−23	2.7
1968	1	32.30	1.67	1.15	2.82	3.7	104	5.0
	2	32.50	1.82	1.13	2.95	4.1	43	4.6
	3	31.10	1.59	1.02	2.61	.2	13	.3
	4	32.18	4.23	.12	4.35	.3	2	.3
1969	1	31.42	3.18	2.53	5.71	1.8	118	3.4
	2	31.54	2.97	2.35	5.32	1.1	55	1.7
	3	30.64	3.29	1.73	5.02	.1	19	.3
	4	30.70	6.11	.27	6.38	.1	−5	.1
1970	1	31.51	2.21	2.14	4.35	11.8	177	14.0
	2	30.82	2.35	1.79	4.14	7.4	171	9.5
	3	28.86	2.19	.37	2.56	<.1	5	.1
	4	28.79	3.99	.13	4.12	.1	<1	.1
1971	1	28.93	2.06	4.94	7.00	20.0	399	25.4
	2	29.02	2.62	3.84	6.46	13.3	241	16.2
	3	29.70	2.84	1.52	4.36	[1].4	[1]30	.6
	4	29.96	5.49	.71	6.20	[1]1.5	[1]6	1.6
1965–71 averages	1	32.58	2.50	4.80	7.30	26.7	500	33.4
	2	32.34	2.52	4.45	6.96	20.9	388	25.5
	3	31.54	2.91	1.75	4.66	.3	40	.6
	4	31.85	6.22	.67	6.89	.9	2	.9

[1] Division between sheet-rill and gully erosion estimated.
[2] Negative value indicates channel fill.

these two subprocesses, and this has impeded the study of the mechanics of gullying.

If gully soil debris is produced predominantly by the shearing forces of flowing water, these forces are also sufficient to entrain and transport this fine-grained loessial debris through the channel system. However, evidence at both watersheds 1 and 2 indicates that the shearing or tractive forces on the channel boundary are not the major forces causing gully erosion. Aside from the visual evidence of gully-head and gully-bank deterioration as shown in figure 2, gully-sediment concentrations and discharges of individual storm events often reached a maximum soon after surface runoff began but rapidly decreased before the peak of storm runoff. In some cases, there was a period near the runoff peak when the supply of soil debris in the gully was exhausted, and the transport of gully materials was essentially zero (fig. 5). The gully-sediment discharge curve of figure 5 is based on 30 streamflow samples. Figure 6 shows the gully-sediment discharge at watershed 1 for one of the runoff events of May 10, 1971, when the gully sediment-concentration curve was defined by 32 samples. This was the first large runoff event of the year. Because it was preceded by minor runoff, there were brief periods at the outset of the storm when there was no gully erosion. Temporary gully cleanout occurred on the hydrograph recession prior to a runoff rate of about 30 ft^3/s. Had tractive force on the channel boundary been the

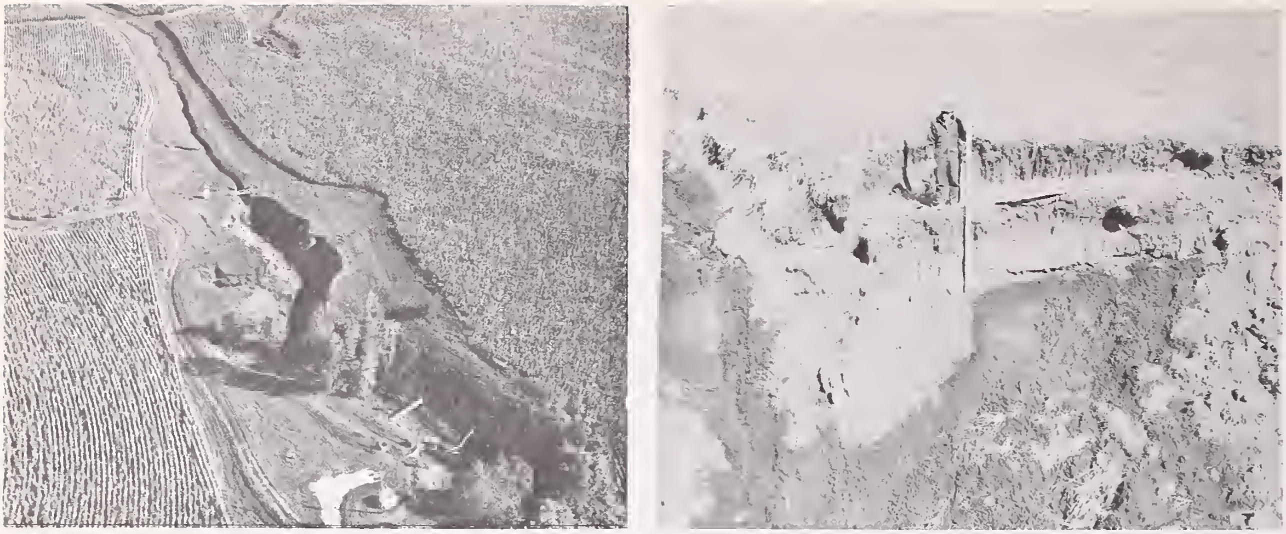
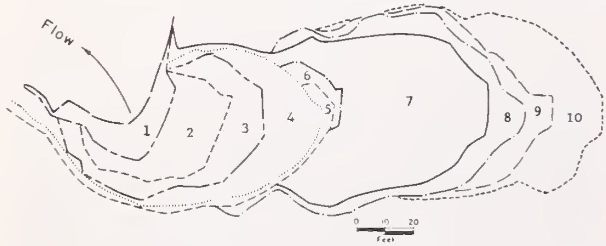


FIGURE 2.—(*Left*) Aerial view of watershed 1 outlet drainageway, showing sampling footbridges and measuring weir. (*Right*) Closeup of gully headcut area, showing portion of upstream drainageway at extreme left, failed soil mass, and seepage.

predominant eroding agent during these storms, either by direct shear on the channel boundary or by bank undercutting, a discharge of gully sediments approximately proportional to the square of stream velocity would have occurred, and zero transport of gully sediments at significant runoff rates would not have been experienced.

Sediment-transport curves (fig. 7) for four successive runoff events at watershed 1 represent the concentration and rate of movement of gully materials with respect to rate of runoff.



Area	Period	Surface runoff (acre-ft)	Gully erosion (tons)
1	Nov. 15, 1964—Apr. 14, 1965	25	130
2	Apr. 15, 1965—June 9, 1965	17	510
3	June 10, 1965—Aug. 13, 1965	12	160
4	Aug. 14, 1965—Nov. 15, 1965	14	350
5	Nov. 16, 1965—July 15, 1966	4	90
6	July 16, 1966—May 30, 1967	1	<10
7	May 31, 1967—June 27, 1967	70	1,440
8	June 28, 1967—Dec. 31, 1969	24	230
9	Jan. 1, 1970—Dec. 15, 1970	13	180
10	Dec. 16, 1970—Dec. 8, 1971	31	400
	Total	211	3,500

FIGURE 3.—Measured gully advances and erosion rates on watershed 1 near Treynor, Iowa.

These were compiled from graphs of sediment concentration versus time that were constructed on the basis of numerous streamflow samples; gully-sediment discharges were computed from

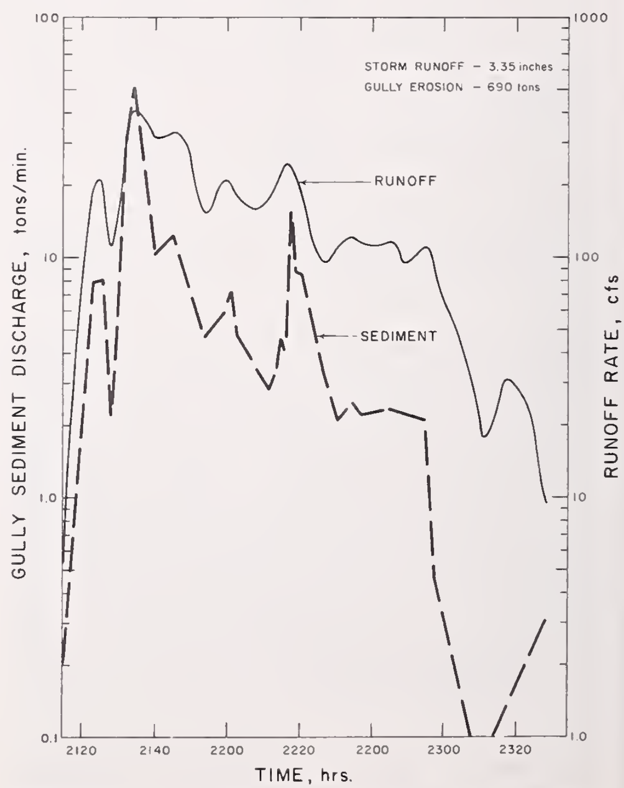


FIGURE 4.—Gully-erosion rate from 700-ft length of channel at watershed 2, June 20, 1967.

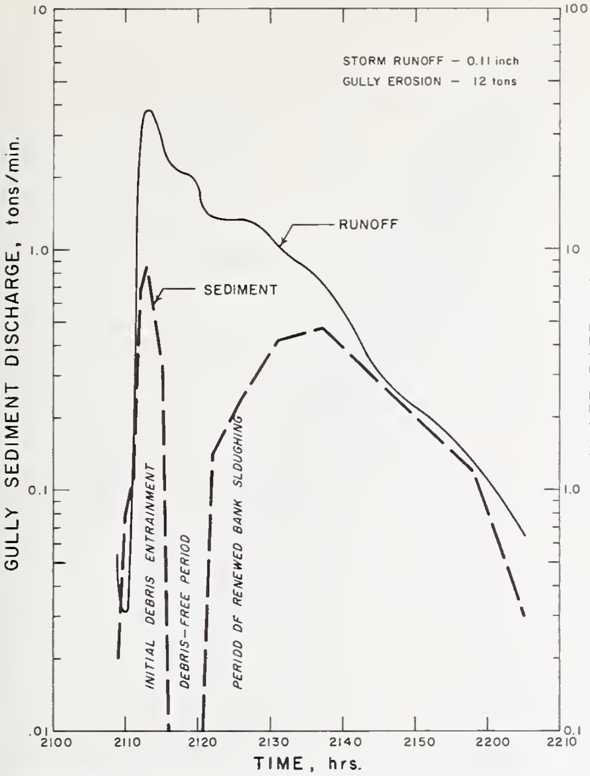


FIGURE 5.—Gully erosion rate, storm of May 25, 1965, at watershed 1.

these graphs. Characteristics of such sediment-transport curves can be summarized from the study of many of these individual sediment-transport curves. For example:

1. The overall relationship of gully-sediment discharge (and concentration) to runoff for any time interval during a storm indicates the availability of gully debris. Generally, dry conditions prior to an event cause higher placement of the upper limb of the curve (higher gully-sediment concentrations) and increase vertical distance between limbs (fig. 7).

2. Cleanout of the gully channel, evidenced by a "break" in the loop in the downward direction, occurs more often when wet conditions exist before a given storm (fig. 7).

3. Renewed erosion, usually caused by sloughing of wetted gully banks, often occurs after the peak of runoff. Although not clearly shown in figure 7 this transport characteristic is often identified on sediment-transport curves by a sharp upward trend. This condition has been noted in other loess areas by the senior author, who has sampled loessial streams at night while suspended from a 40-ft-high overhead cable and has relied on the sound of massive bank segments crashing into the water to indicate that the water stage was beginning to fall.

The effect of prior moisture conditions on gully erosion rates is illustrated by the sediment-transport curves for the four successive events of figure 7. Numerical entries on the lower curve of each graph denote 24-h clock time. Note that debris cleanout was not effected until early in the third runoff event, and bank sloughing occurred just before 4:31 a.m. and again after 4:39 a.m. A comparison of events 1 and 4, which have similar runoff rates, dramatizes the effect of debris cleanout; the gully-sediment concentration exceeded 50,000 p/m for the first event but did not exceed 15,000 p/m during the fourth event because debris supply was limited.

Interpretations Based on the 7-Year Composite Sample Record

Additional insights into processes that affect gullying at Treynor can be obtained by referring to the composite 7-yr streamflow-sample record

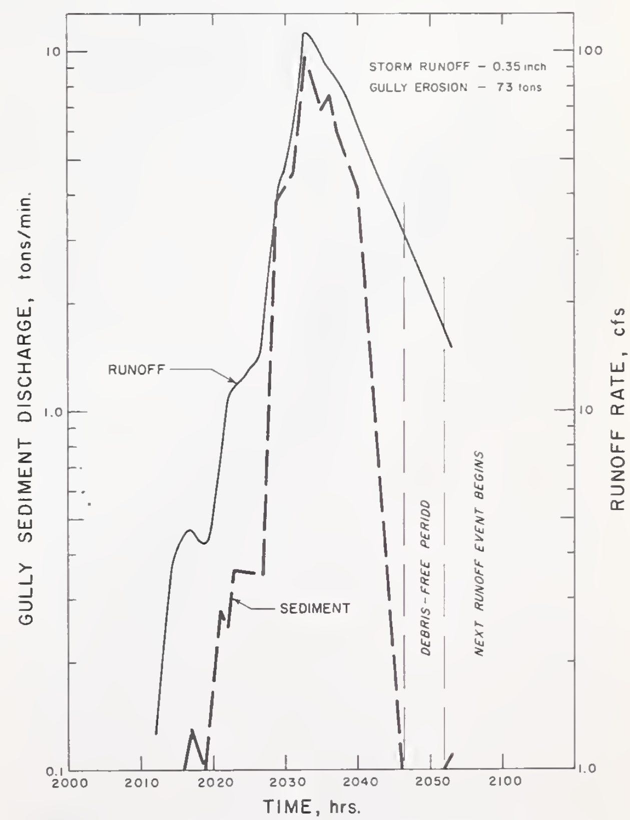


FIGURE 6.—Gully sediment discharges during the first large runoff event of 1971 at watershed 1.

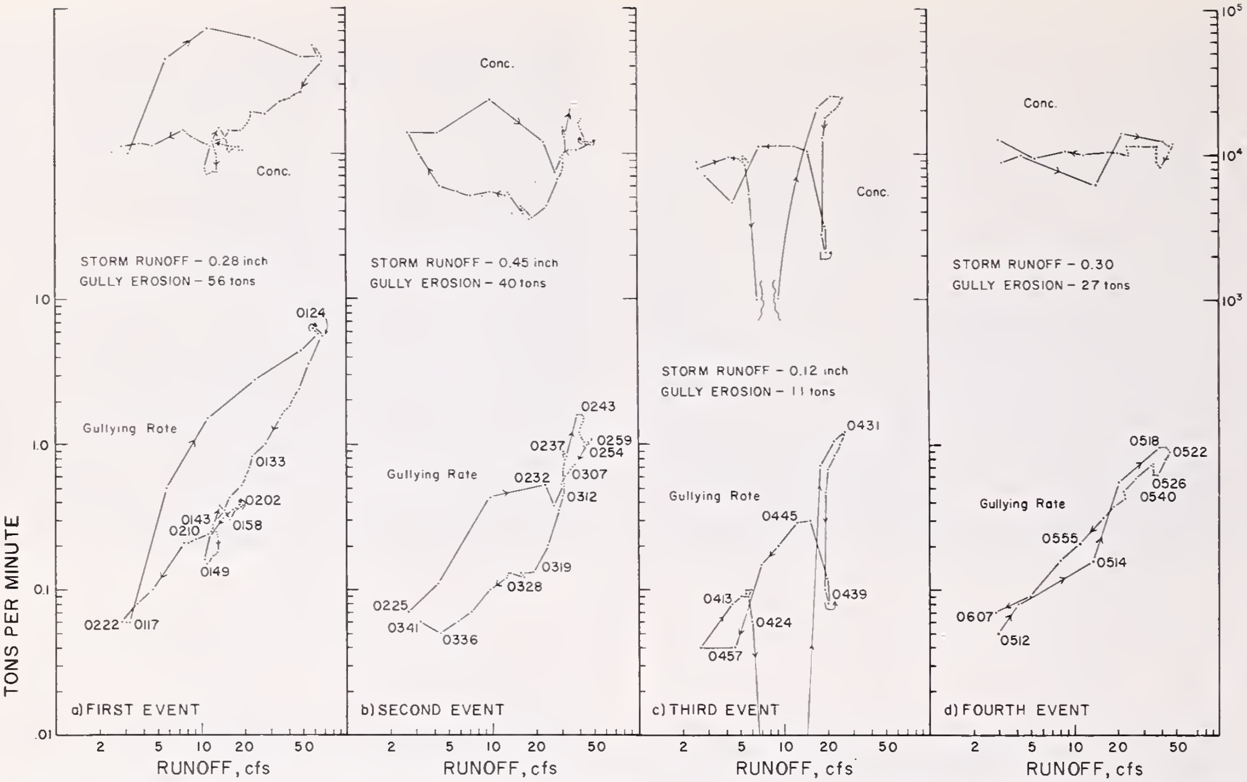


FIGURE 7.—Gully-sediment transport relations for successive runoff events of September 7, 1965, watershed 1, near Treynor, Iowa.

for the two locations at the outlet of watershed 1. The 1,042 streamflow samples of figure 8 were collected just above the retreating gully head; the 1,653 samples of figure 9 were collected downstream from the gully head. All of the runoff that reached the downstream sample point also passed over the gully headcut, except for the small portion generated by rain falling in the gully. Statistics of the relationship, including the least-squares regressions, are given on the figures. The same least-squares analysis for watershed 2 (not shown) results in the equations $Q_s=11.6Q_w^{1.64}$;$R^2=0.89$ (upstream from headcut); and $Q_s=30.7Q_w^{1.53}$;$R^2=0.94$ (downstream from headcut). In each case, the sediment discharge, Q_s, is in lb/min and water discharge, Q_w, is in ft^3/s. The difference between the curves of figures 8 and 9 gives the overall relation between gully erosion and runoff rates for the period of record, because it reflects all sample data. This net relation between gully-sediment discharges and runoff rates for watersheds 1 and 2 is given in figures 10 and 11, respectively. The trend lines shown were derived from the forced linear fit of data, such as figures 8 and 9, and a more correct curve-fitting procedure by which all values of the dependent variable were averaged for successive, small increments of the independent variable and a best-fit curve drawn through these group averages.[6] In either procedure, the shapes of the resulting curves (fig. 10) and the basic conclusions to be drawn from a comparison of the curves are not significantly changed. That is, the gully-sediment discharge curve defined by samples for watershed 1 is not as steep as that for watershed 2, and the concentration at watershed 1 increases to a peak value at intermediate runoff rates and decreases thereafter. The watershed 2 gully sediment concentration, by contrast, increases throughout the entire range of runoff. Curve 10, for the gully of watershed 1, represents an actively eroding headcut and an average 350-ft channel (table 1), and curve 11, for the gully of watershed 2, represents a slightly eroding headcut and a 700-ft channel;

[6] American Society of Civil Engineers, Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation of the Hydraulics Division. 1970. Sediment measurement techniques: Chapter IV, Sediment sources and sediment yields. Journal of the Hydrology Division, Proceedings of the American Society of Civil Engineers 96 (HY6): 1283–1329.

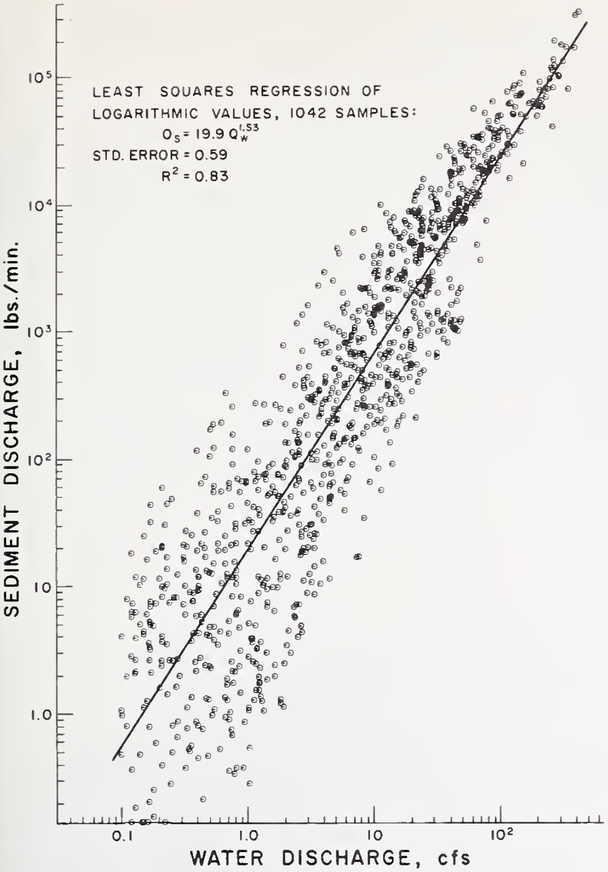


FIGURE 8.—Sediment transport relation representing sheet-rill erosion at watershed 1.

therefore, we can conclude that the sustained gully sediment concentrations of watershed 2 originate from the channel bank. Conversely, headcut erosion at watershed 1 is not enough to sustain a high rate of increase in gully-sediment transport as would be expected if tractive forces were mostly responsible for headcut erosion. The stabilization and decrease in gully-sediment concentration with increasing runoff at watershed 1 are a consequence of cleanout of headcut materials at moderate runoff rates.

Interpretations Based on Measured Runoff and Gullying, by Storm

The foregoing conclusion—that gully sediment-runoff relations differ according to whether gully head or gully bank erosion is occurring—is also verified if gully erosion is considered on a storm-event basis. Each of the plotted points of figure 12 represents a single storm that was adequately sampled. (For the 7-yr period, 1965–71, this included 52 events at watershed 1.) That is, dual sediment-concentration graphs, derived from streamflow samples collected upstream and downstream from the gully headcut, were well defined. The sediment discharge that originated from the gully was then calculated; this storm gully discharge, divided by the storm runoff and the appropriate conversion constant, is termed a runoff-weighted gully-sediment concentration. Figure 12 shows considerable scatter in gully-sediment concentration for watershed 1 storm events, and statistical analyses show that sediment concentration is not well correlated with runoff, although the same slight trend of decreasing concentration with increasing runoff is apparent. This is to be expected, since the concentration curve of figure 10 for the watershed 1 gully does not consistently increase with increasing runoff rate.

Sediment concentration is usually considered to be a better erosion indicator than sediment discharge for testing with erosion-causing variables, for two primary reasons:

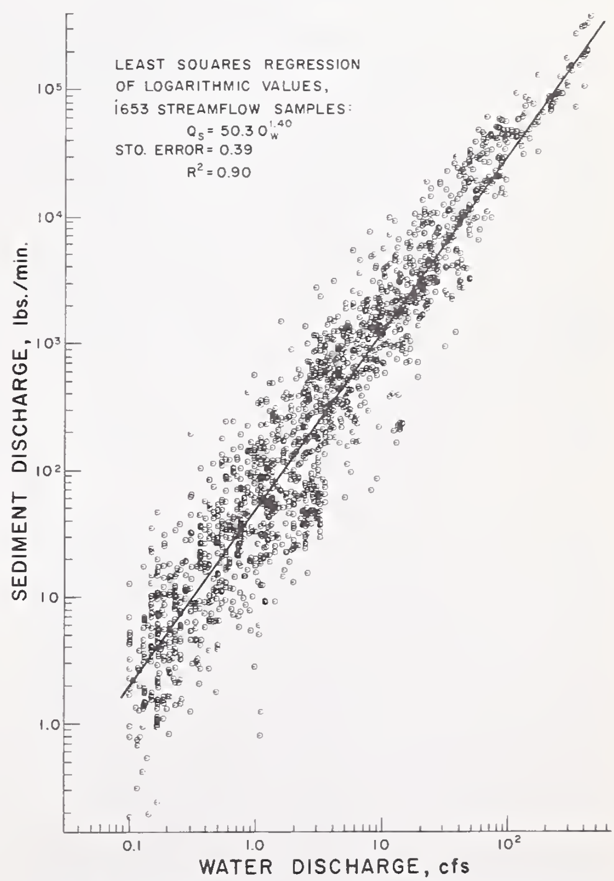


FIGURE 9.—Sediment transport relation representing sheet-rill and gully erosion at watershed 1.

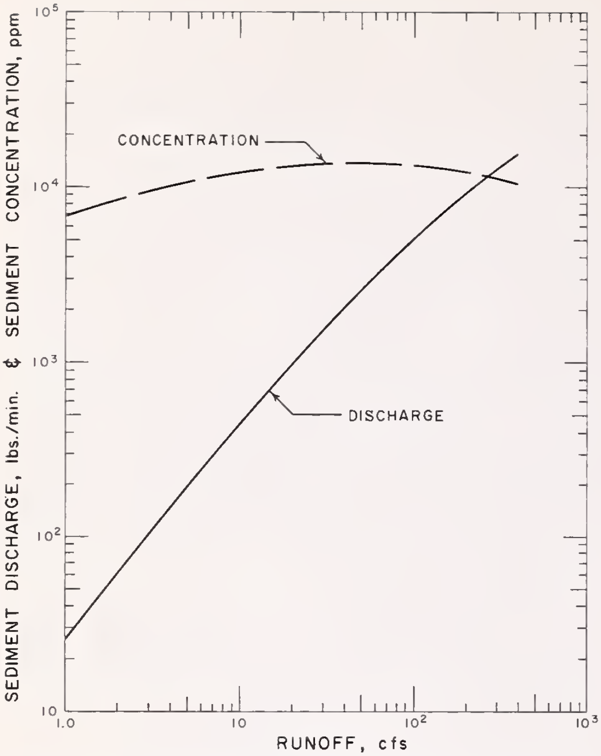


FIGURE 10.—Sediment transport relation for gully of watershed 1, based on 2,700 streamflow samples.

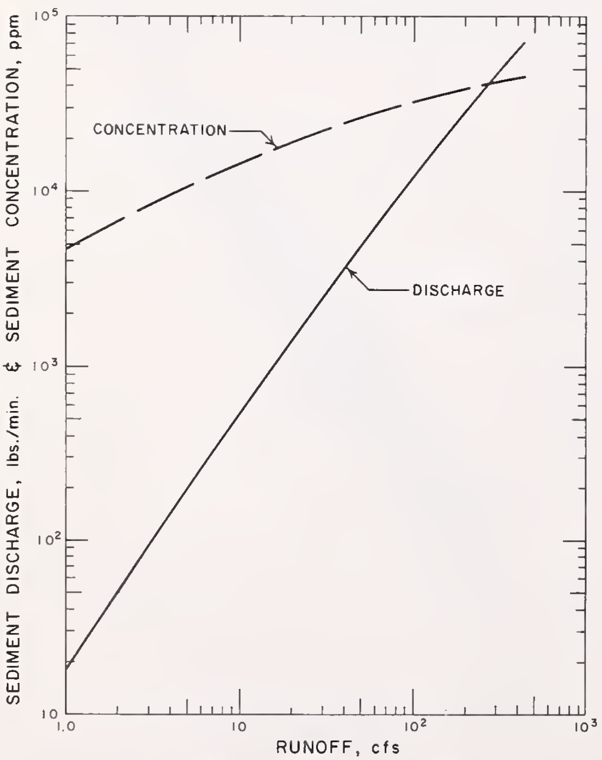


FIGURE 11.—Sediment transport relation for gully of watershed 2, based on 2,500 streamflow samples.

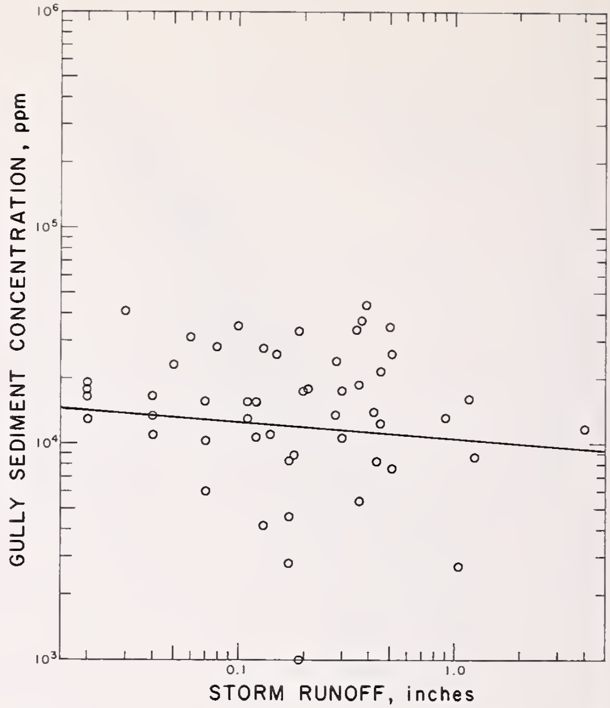


FIGURE 12.—Storm runoff versus runoff-weighted sediment concentration from gully erosion, using all well-sampled runoff events at watershed 1, 1965–71.

1. The product of runoff and sediment concentration is sediment discharge, so there is a statistical bias built into any relationship that may be runoff-correlated.

2. Runoff is not a basic variable. Because it is usually well correlated with the erosion parameter, its use tends to mask the effect of more subtle basic environmental variables on sediment production.

The objective of this study was to obtain a gully erosion relationship for predictive purposes as well as to isolate variables causing erosion, so both the gully-sediment concentrations and sediment discharges of watersheds 1 and 2 were examined. Figures 13 and 14 show the log-linear relationships between gully-sediment discharge and runoff, on a storm basis, for watersheds 1 and 2. At watersheds 1 and 2, storm runoff volume alone was sufficient to explain 70 and 78 pct, respectively, of the variation in storm gully-erosion rate. However, the accuracy of prediction was not especially good. In round numbers, the actual gully-sediment discharge for a storm of known runoff volume will be 50 to 200 pct of the predicted value two out of three times.

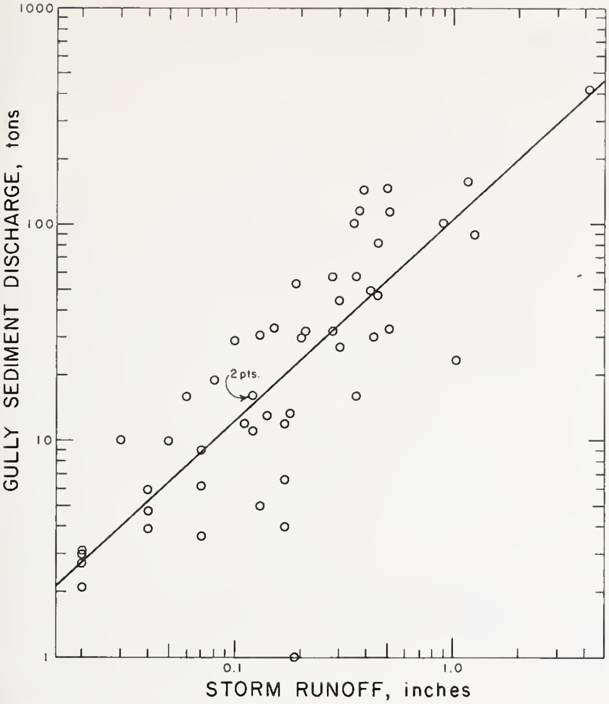


FIGURE 13.—Relationship between runoff and gully sediment discharge, by storm, at watershed 1, 1965–71.

This information has even less value when applied to another gully.

To improve the prediction equations and to examine the effect of environmental factors on gully erosion, the following variables were tested for the 52 well-sampled storms at watershed 1 and the 41 well-sampled storms at watershed 2.

1. Peak storm runoff, inches per hour.
2. Average soil moisture (before each storm) in the 2- to 6-ft profile, inches. These were determined from approximately weekly readings at six sites on the two watersheds.
3. Change in these soil-moisture levels from storm to storm, inches.
4. Ground-water well level before each storm for a single well near each gully head, feet. These were based on well-level recorders during part of the study and periodic tapedowns for the remainder of the time.
5. Change in well levels from storm to storm, feet.
6. Change in well level from the April 1 well level, feet.
7. Season. Each storm was represented by the Julian date on which it occurred. Snowmelt data were excluded.
8. Time. Each storm was represented by the numerical day of the period, beginning with January 1, 1965.
9. Time, hours, since prior precipitation event which exceeded one-half inch.
10. Time, hours, since prior event which exceeded 0.01 inch of runoff (volume).
11. Time, hours, since prior event when runoff peak exceeded 0.5 ft^3/s.

These variables were selected because the weathering of gully walls and headcut is logically related to moisture and seasonal changes occurring between rainstorms.

Stepwise multiple regression-correlation computer analyses were made using these variables. For some analyses, runoff amount, peak rate, and time were deleted because they proved to be best correlated and probably masked the effectiveness of other intercorrelated variables. A brief summary of the attempt to define variables influencing gully erosion is given here for watershed 1.

Dependent variable	*Variables tested*	*Explained variation,* R^2
Gully sediment, storm tonnage.	Storm runoff volume	0.70
Do	All eleven	.79
Do	All except runoff volume and peak.	.21
Do	All except time	.76
Do	All except time, runoff volume, and peak.	.21
Gully sediment, storm concentration, p/m.	Runoff volume	.24
Do	All eleven	.43
Do	All except runoff volume and peak.	.18
Do	All except time	.09
Do	All except time, runoff volume, and peak.	.09

Results of these tests show that the expressions used to represent environmental factors do not greatly improve the relation between runoff and gully erosion. This is puzzling because other techniques show the erosion effectiveness of successive storm events to be drastically different.

Interpreting the Effect of Interrelated Season-Soil Moisture Variables on Gully Erosion Rates, May 1971

For example, consider the successive storm events of May 6, 10, and 18, 1971, at watershed 1, which were very well sampled. Runoff-duration

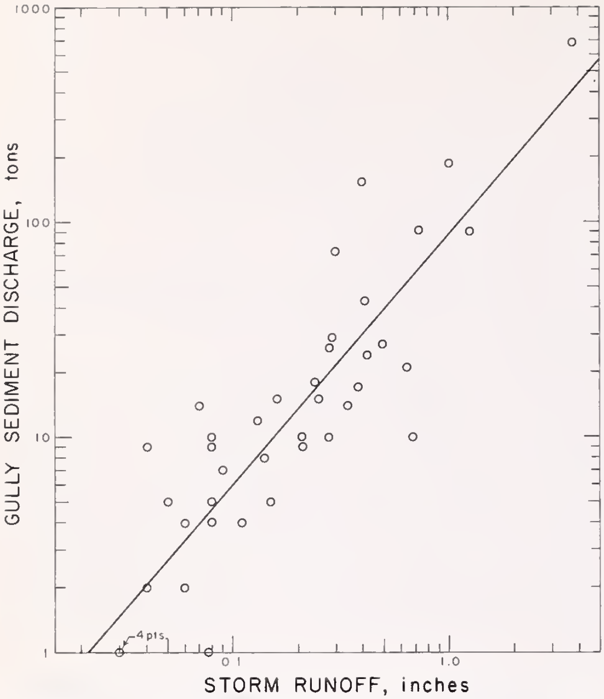


FIGURE 14.—Relationship between runoff and gully sediment discharge, by storm, at watershed 2, 1965–71.

information for these storms appears in table 3, and the gully-erosion rates are computed using the average runoff-sediment discharge relation of figure 10. These computed values were compared with measured gully-erosion rates for the same storm. The May 6 storm was the first significant runoff event of 1971, and the May 18 storm occurred near the end of a wet period. Table 3 shows that the runoff-weighted sediment concentration of streamflow that is due to gully erosion is greater for the May 10 storm (16,100 p/m) than for the May 18 storm (3,700 p/m). The May 6 gully sediment concentration was highest at 20,200 p/m. This decrease in concentration with time was almost certainly caused by cleanout of existing gully debris and the occurrence of the May 10 and 18 storms before much additional debris could accumulate.

With average antecedent conditions as represented by the curve of figure 10, the same runoff that occurred May 6 would be expected to produce 30 tons from the gully instead of the measured 58 tons, at a concentration of 10,400 p/m instead of 20,200 p/m. By contrast, the high rainfall and runoff of May 18 would be expected to erode 153 tons from the gully of watershed 1, instead of the measured 46 tons, if average environmental conditions prevailed. Such differences probably explain much of the scatter in figures 13 and 14.

Miscellaneous Interpretations

To this point, the interplay of basic forces that cause the gully walls to fail eludes us. We have dealt principally with rates of sediment movement from the gully in terms of runoff and similar composite variables that concern the total gully process and have not included physical or mechanical measurements needed for a study of massive soil failures. A paper by Bradford, Farrell, and Larson[7] considers the stability of gully banks by analyzing the forces acting on the soil mass that forms the gully walls. The two-dimensional stability analysis using the simplified Bishop method of slices to calculate critical factors of safety indicates that height of water table, cohesion of soil and rate of water infiltration are controlling factors affecting stability of gully walls.

Any factor that alters the potential resisting forces of the soil (available shearing strength) and the driving forces will influence the failure of the gully walls. The soil-modifying effects of winter freezing and spring thawing—and wetting and drying cycles—influence soil shearing strength. These weather-caused stresses are difficult to evaluate in a limited field study. Total gully erosion from snowmelt has been negligible on the Treynor watersheds, although much of the damage to gully banks from freezing and thawing cycles probably contributes to gully growth during the first spring runoff event, as previously shown for watershed 1 on May 6, 1971. Figures 15 and 16 illustrate that snowmelt gully-erosion rates are consistently and significantly higher at watershed 1 than at watershed 2, whether the snowmelt occurs on frozen or thawed ground. These erosion differences can hardly be due to differences in tractive force but are probably related to a more erosive plunge pool action on watershed 1. Also, the gully overfall at watershed 1 faces south, and watershed 2 gully head faces west. A south-facing slope is subject to more frequent wetting-drying and freezing-thawing cycles.

[7] Bradford, J. M., Farrell, D. A., and Larson, W. E. 1973. Mathematical evaluation of factors affecting gully stability. Proceedings of the Soil Science Society of America 37(1): 103–107.

TABLE 3.—*Gully erosion for successive storms, based on average antecedent conditions at watershed 1*[1]

May 6, 1971					May 10, 1971					May 18, 1971				
Runoff interval (ft^3/s)	Duration (min)	Mean runoff rate (ft^3/s)	Mean gully-erosion rate (lb/min)	Gully erosion (lb)	Runoff interval (ft^3/s)	Duration (min)	Mean runoff rate (ft^3/s)	Mean gully-erosion rate (lb/min)	Gully erosion (lb)	Runoff interval (ft^3/s)	Duration (min)	Mean runoff rate (ft^3/s)	Mean gully-erosion rate (lb/min)	Gully erosion (lb)
0 – .1	942	0.05	0.4	377	0 – .1	936	0.05	0.4	374	0 – .1	568	0.05	0.4	227
.1– .5	225	.3	5.5	1,238	.1– .5	156	.3	5.5	858	.1– .5	379	.3	5.5	2,084
.5– 1.0	63	.75	18	1,134	.5– 1.0	61	.75	18	1,098	.5– 1.0	110	.75	18	1,980
1 – 2	37	1.5	44	1,628	1 – 2	68	1.5	44	2,992	1 – 2	126	1.5	44	5,544
2 – 3	24	2.5	81	1,944	2 – 5	47	3.5	123	5,781	2 – 5	45	3.5	123	5,535
3 – 4	21	3.5	123	2,583	5 – 10	26	7.5	305	7,930	5 – 10	24	7.5	305	7,320
4 – 5	23	4.5	165	3,795	10 – 15	12	12.5	550	6,600	10 – 20	82	15	680	55,760
5 – 6	19	5.5	210	3,990	15 – 20	19	17.5	810	15,390	20 – 40	32	30	1,490	47,680
6 – 7	20	6.5	255	5,100	20 – 25	19	22.5	1,080	20,520	40 – 60	10	50	2,540	25,400
7 – 9	18	8	330	5,940	25 – 30	22	27.5	1,350	29,700	60 – 80	5	70	3,520	17,600
9 –11	16	10	430	6,880	30 – 35	16	32.5	1,620	25,920	80 –100	4	90	4,500	18,000
11 –13	12	12	530	6,360	35 – 40	14	37.5	1,890	26,460	100 –120	2	110	5,450	10,900
13 –15	6	14	630	3,780	40 – 45	10	42.5	2,150	21,500	120 –140	3	130	6,350	19,050
15 –18	2	16.5	760	1,520	45 – 50	5	47.5	2,410	12,050	140 –160	2	150	7,150	14,300
18 –21	3	19.5	910	2,730	50 – 60	5	55	2,780	13,900	160 –180	2	170	7,950	15,900
21 –24	3	22.5	1,080	3,240	60 – 70	8	65	3,290	26,320	180 –200	0	190	8,700	0
24 –27	3	25.5	1,240	3,720	70 – 80	7	75	3,780	26,460	200 –220	3	210	9,400	28,200
27 –30	2	28.5	1,400	2,800	80 – 90	2	85	4,250	8,500	220 –240	3	230	10,100	30,300
30 –33	1	31.5	1,560	1,560	90 –100	3	95	4,740	14,220					305,780
				60,319	100 –110	0	105	5,250	0					
					110 –120	1	115	5,650	5,650					
					120 –130	1	125	6,100	6,100					
					130 –140	2	135	6,550	13,100					
									291,423					

[1] Comparison of actual measured rates with computed rates:

	May 6, 1971	*May 10, 1971*	*May 18, 1971*
Computed gully erosion ....tons......	30	146	153
Measured gully erosion ....tons......	58	186	46
Weighted gully-sediment concentration..p/m......	20,000	16,100	3,700
Runoff ....inches......	0.34	1.37	1.47

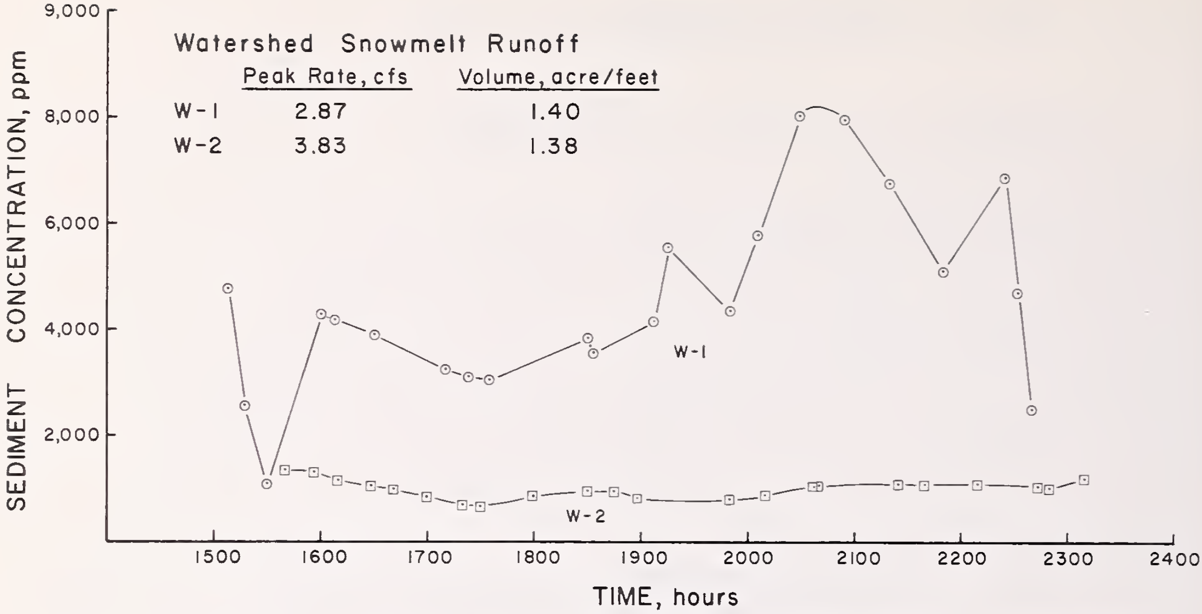


FIGURE 15.—Gully-sediment concentration for event of January 15, 1969, watersheds 1 and 2, frozen topsoil.

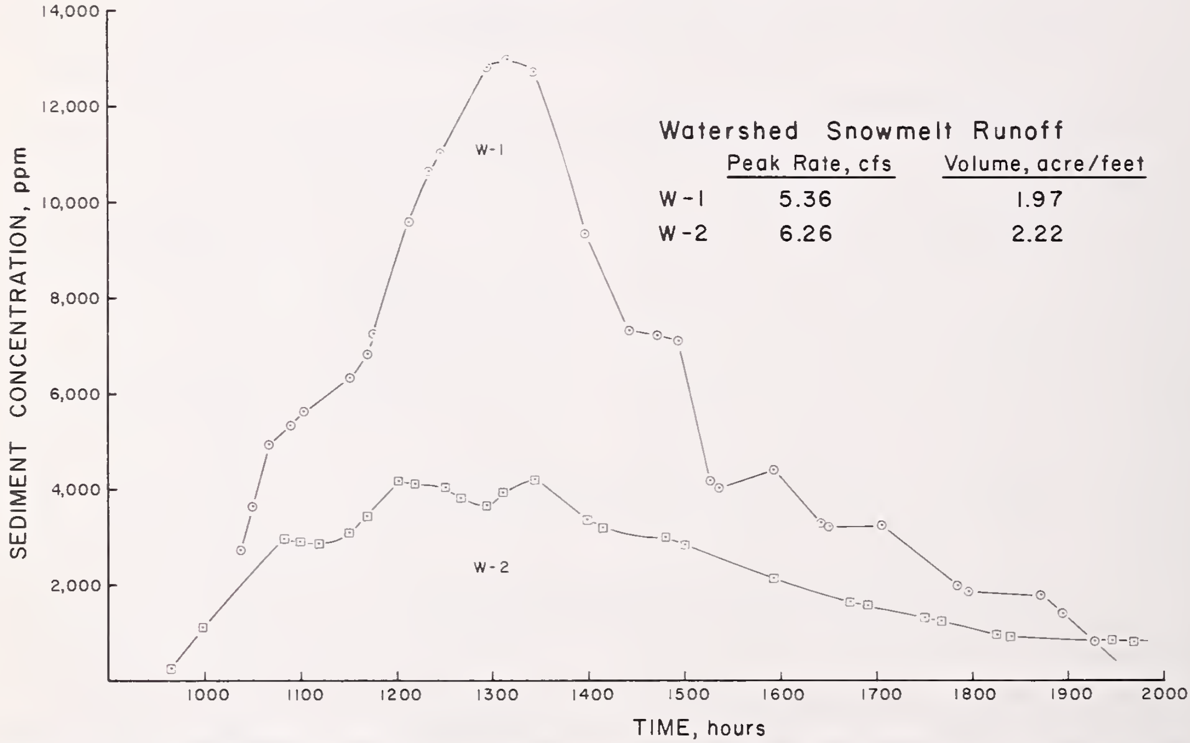


FIGURE 16.—Gully-sediment concentration for event of February 25, 1969, watersheds 1 and 2, thawed topsoil.

CONCLUSIONS

Neither the geologist's explanation of the cause of gullying nor the limited findings noted herein—that runoff rates at Treynor are the best indicators of gully erosion rates—give much insight into basic erosion mechanisms. But there is some common ground for these findings. The concepts that wetter climatic trends during geologic time (in the midcontinent region) slowed

gullying rates and that land abuse in the past dozen decades has accelerated gully erosion are really telling the same story—the balance between runoff and vegetative levels is all-important. Langbein and Schumm[8] utilized sediment records to show that erosion levels increase as the climate changes from humid to arid, up to the point where the lessened runoff rates, rather than the deteriorating vegetal cover, would inhibit further increases in erosion. Historic man has, in many respects, created a new climate in which increased runoff rates and decreased vegetal cover combine to accelerate gully erosion.

Surface runoff rates from conservation watersheds 3 and 4 are drastically reduced, compared with watersheds 1 and 2. The channels of these conservation watersheds have responded to treatment by remaining stable, as figure 1 demonstrates. A flow rate of 40 ft^3/s in the gully of watershed 4 did not upset the stable channel condition, and only a record storm at watershed 3 could cause significant gully erosion there. Apparently the combination of favorable runoff regimen and suitable channel vegetal cover at these watersheds is sufficient to stabilize the gullies unless some seemingly chance occurrence (or combination of occurrences) takes place, such as record runoff, devegetated channel, or critically located rodent burrows.

It would require a significant reduction in surface runoff at watersheds 1 and 2 to bring about stable conditions there, but consider the effect of some conservation practice that would not affect storm runoff volumes but would reduce the runoff rates by one-half and double the flow duration. Based on the sediment-transport relationships at these watersheds, a 50-pct runoff-rate reduction would not decrease gully-head erosion (and would probably increase it somewhat) if the trends of figures 10 and 13 are typical. That this change in runoff would fail to deter gully-head erosion is well recognized by farmers who have tried to empty the outflow from small reservoirs gently into a loessial channel and suffered dire consequences. We have ample proof for the statement that gully-head erosion can be initiated and sustained by moderate runoff rates once a minimum (but unknown) rate is exceeded.

[8] Langbein, W. B., and Schumm, S. A. 1958. Yield of sediment in relation to mean annual precipitation. Transactions of the American Geophysical Union 39(6): 1076–1084.

The effect of a 50-pct runoff-rate reduction on channel-bank erosion would be great. Based on the experience at watershed 2, as shown by the sediment-transport curves of figures 11 and 14, we would expect a sizable reduction in gully erosion rates. The authors' interpretations of the effect of these assumed runoff regimes on gully-head and gully-bank erosion can be questioned on the grounds that channel debris cleanout has occurred at both locations. Gully-bank erosion at Treynor watershed 2 was measured for only a 700-ft channel, however, and active gully enlargement is no doubt occurring over a greater length downstream.

The terminal geometry (final dimensions and slopes) of the gullied channels at Treynor can probably be fixed within close limits for any given channel cross section, because the critical dimension, depth to glacial till, is known. The ultimate width can also be forecast for differing runoff regimes if our present concepts of soil stability mechanisms are valid. Although the depth of bank failure seems related to the location of the seepage plane (fig. 3), it is improbable that the seepage plane affects the total masses eroded, because the trenching depth is still the governing variable. The effect of gully-bank seepage on erosion rates is probably much greater at locations where the trenching depth is not controlled by resistant soil or rock.

Subsurface soil-moisture content, well levels, storm antecedent conditions, and seasonal and time trends were tested for correlation with gully-erosion rates. Results were not encouraging, possibly bcause many of the variables may be well correlated with soil slippage mechanisms (which cannot be expressed in this field experiment) but not the sediment-removal process. Using a different analytical approach (table 3), the effect of prior moisture conditions for successive rainstorms is clearly illustrated; the May 18, 1971, event with wet prior conditions, for example, caused only one-third of the gully erosion that would occur under average moisture conditions (a measured 46 tons versus a computed 153 tons).

Unstable blocks of soil seem to appear at random along the gully banks in response to unmeasured forces. Our present understanding of the failure sequence is that moisture saturation, mostly by runoff and possibly by a heavy rain-

fall, causes loss of soil strength and block dislocation by slippage. The importance of this mode of gully-bank deterioration and failure has only recently been appreciated by the authors, who have noted the formation of nick points along channels caused by runoff from tiny drainage areas infiltrating the soil block at the channel edge through heavily sodded grass. Gradual undermining and occasional block overturning accounts for its migration downslope to the point of eventual entrainment. Other mass supply mechanisms may be initiated by streamward displacement of soil blocks caused by lateral pressures released in the gully cutting process—and by shrinkage cracking.

Tractive forces do not play the major role in the erosion of these valley-head gullies. That is, the resistance of the channel boundary to erosion exceeds the erosive power of the runoff under most circumstances. The erosive power of runoff plays a minor role in gully growth in the loess study area, except for its relation to transport of eroded bank material—and possibly some plunge pool action.

SOURCE OF SOIL ERODED BY WATER FROM UPLAND SLOPES[1]

By L. D. Meyer,[2] G. R. Foster,[3] and M. J. M. Römkens[4]

Identification of the sources of sediment is important in developing methods of reducing soil loss from upland areas, for evaluating the pollution potential of eroded soil, for developing a comprehensive mathematical soil-erosion model, and for broader application of research results. Past erosion research usually has not determined whether soil that was eroded from upland slopes originated from the soil surface or from beneath it, whether it was lost relatively uniformly over the entire area or primarily from certain parts of the slope, or whether the erosion resulted mainly from raindrop impact or from flowing runoff. Instead, erosion research has been directed primarily toward determining the quantity of soil delivered to a specific point or toward designing practices for reducing the quantity of soil lost. The physical, chemical, and biological characteristics of the eroded material have received little attention. Such information is important to researchers and to application conservationists.

Several series of experimental studies were conducted at West Lafayette, Ind., to obtain data on sediment sources and factors affecting them. The results form the basis for significant progress in understanding and controlling soil erosion by water.

THE PROCESS OF SOIL EROSION BY WATER

The soil erosion-sedimentation process involves detachment of soil particles (primary and aggregated) from the soil mass, transportation of these particles downslope, and their eventual deposition. Individual particles may undergo this series of events many times, and final deposition may be beyond the upslope area. Impacting raindrops and flowing water are the erosive agents that work against the resisting forces of gravity and cohesion to detach and move the particles.

The erosion process normally begins when raindrops strike the soil surface. The explosive character of impacting raindrops detaches soil particles from the soil mass. The detached particles are splashed in all directions from the impact points, with net movement downslope.

Conceptually, all rainfall is infiltrated so long as the infiltration capacity exceeds the rainfall rate. Once rainfall rate exceeds the infiltration rate, the excess water begins ponding because of land microrelief (surface storage). If the excess rainfall rate continues long enough, overland flow (surface runoff) begins. Overland flow normally flows for a short distance at a shallow (thin-film) depth. This prerill type of runoff is termed interrill flow. As overland flow moves downslope, it tends to concentrate because of tillage marks, natural microtopography, or previous erosion. These flow concentrations are called rills, and the runoff occurring in them is termed rill flow (*3*).[5] As the flow continues

[1] Cooperative research of the Agricultural Research Service, U.S. Department of Agriculture, and the Purdue Agricultural Experiment Station. Purdue Journal Paper No. 4917.

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[5] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this paper.

downslope, erosion by rilling progresses, and rill patterns develop on sloping land.

This concept of upland runoff suggests dividing the erosion process into source areas of interrill erosion (erosion on surfaces where interrill flow occurs) and rill erosion (erosion occurring within the concentrated flow areas). Such a division is very useful in mathematical simulation of the soil erosion process, as shown by Foster and Meyer (*7*). Furthermore, in conducting experimental research, it enables a meaningful separation of the sources of eroded soil into the portion coming from the very top of the soil surface on the interrill areas and the portion from a relatively greater depth in the rills.

Four erosion subprocesses have been recognized as possible on both the interrill and rill source areas of an eroding slope: soil detachment by rainfall, transport by rainfall, detachment by runoff, and transport by runoff (*12*). The relative importance of each varies greatly, depending on the conditions. Therefore, knowledge of the significance of each for specific situations is essential for accurate prediction of sediment yields and for design of effective erosion-control practices.

On the interrill areas, the several effects of raindrop impact usually are the dominant factors influencing erosion rate. Research on a 2- by 2-ft soil pan showed that essentially all soil from such areas is loosened by raindrop impact. When three layers of window screen were placed over the soil pan to dissipate raindrop impact, the total soil loss was less than 10 pct of the loss that occurred when raindrops struck the soil surface directly. Thus, thin film flow on interrill areas has very little detachment capacity in the absence of raindrop impact. Based on related research, its capacity to transport particles is also decreased. However, in the presence of rainfall, the transport capacity of interrill flow is greater and most of the soil detached on interrill areas is transported by the flow.

Raindrop splash normally accounts for only a small part of total soil movement. Soil-pan data suggest that the percentage of total interrill erosion splashed directly to rills is approximately equal to the percentage of the land surface that is rilled, for areas with light to moderate rilling. Thus, if rills cover 10 pct of the soil surface, approximately 10 pct o fthe eroded soil will be splashed to the rills, and the remaining 90 pct will be carried there by interrill flow. Furthermore, when the soil surface is well covered by a canopy that dissipates raindrop impact, soil movement by splash is usually insignificant.

Runoff characteristics are dominant in determining the rill-erosion rate. Rill erosion begins when the eroding capacity of the flow at some point exceeds the ability of the soil particles to resist detachment by flow. Once rilling begins, the concentrated flow tends to enhance the detachment capabilities in that vicinity, and rilling progresses. Rill development often proceeds upslope as headcuts. Successive headcuts commonly exist along a rill, and the local erosion at each is very intense because of the erosive overfall condition. Where headcuts develop, they apparently contribute the major portion of the soil being lost from the rill. However, rill erosion may occur without major headcuts as a relatively uniform increase in the erosion rate with distance along the rill.

Rill erosion on sloping areas may vary from essentially no noticeable rilling to deep, frequent rills. The extent of rilling and the type of rill patterns that develop on sloping land depend on soil properties, slope steepness and other topographic characteristics, runoff rate, and tillage. An interrelationship between detachment by runoff and sediment load has been proposed (*4*):

$$\frac{\text{Detachment rate by flow}}{\text{Detachment capacity of flow}} + \frac{\text{Sediment load in flow}}{\text{Transport capacity of flow}} = 1$$

On most slopes with cohesive soils, calculations suggest that the transport capacity of rill flow is much greater than the rate at which such flow can detach soil. Therefore, detachment rate will normally limit erosion rate. Quite commonly, the estimated sediment load is only a small percentage of the computed transport capacity for slopes of moderate steepness (*4, 5*). However, on noncohesive soils or at locations where the transport capacity decreases considerably, the sediment load may approach the transport capacity. When this occurs, the detachment rate of the flow will be reduced (*4, 18*). If the sediment load exceeds the transport capacity, deposition (negative detachment) occurs. The rate of deposition will depend on the relation between the sediment-carrying capacity and the sediment load of the

flow at a given location (2, 4). Decreased transport capacity results when the slope flattens, the flow channel widens, ponding occurs, or flow is retarded by surface mulches or vegetation.

The influence of these various components of the soil-erosion process can be observed on eroded fields. On upslope areas, where there is no evidence of significant flow concentration or rilling, raindrop detachment is satisfying the transport capacity of the interrill flow, or the detachment capacity of the flow is not sufficient to detach a significant amount of soil from the soil mass. Where rills develop, the detachment capacity of the flow exceeds the ability of the soil to resist detachment, and the transport capacity of the flow is unfilled by raindrop-detached particles. If rills have alluvial fans, these are locations where the transport capacity was not sufficient to carry the sediment load, and deposition resulted. Such observations indicate magnitudes of the erosion hazards at specific locations on upland slopes and suggest the source of the soil that is eroded from the different portions of the slope.

FACTORS THAT AFFECT THE SOURCE OF ERODED SOIL

Various factors influence the erosiveness of rainfall relative to that of runoff, the contribution of interrill erosion sources relative to rill erosion sources, and the rate of soil loss at different locations along a slope. The following discussion indicates effects of rilling, slope length, slope steepness, and several other factors on the source of eroded soil as shown by studies at Purdue and from limited published information.

Influence of Rilling

The susceptibility of sloping soil to rilling affects both the total quantity of eroded soil and the location on the slope where the soil originates. Adjacent 12- by 35-ft plots on Russell silt loam were enlightening regarding the influence of rilling. Both plots appeared identical when ready for testing, but plot R-3 was three times more erodible than plot R-4 because of management differences during the preceeding year. Plot R-3 had been subjected to periodic rainstorms totaling nearly 20 inches of intense simulated rain during the previous summer and had been kept covered by plastic between such applications. The rain caused much soil loss, and the plot remained in a condition comparable to a tropical environment during most of that summer. Although very dry when plowed the following summer, this plot plowed mellow. In contrast, plot R-4 had no tillage during the previous summer and developed a heavy growth of native vegetation. It plowed very cloddy and had to be plowed twice and irrigated before it could be worked into a seedbed condition.

By the time the plots were prepared for rainulator (rainfall simulator) tests, they looked identical, but their erodibility differed drastically. Plot R-3 rilled rapidly and large rills developed, beginning within a few feet of the top of the plot. Soil loss totaled 1169 lb from the 5 inches of intense simulated rain. In contrast, plot R-4 showed no evidence of rilling for the top 20 ft, and only minor rills developed beyond that point. During the identical series of rainstorms applied on R-3, R-4 lost only 346 lb of soil. Runoff on rilled R-3 was only 7 pct more than for unrilled R-4.

Interrill erosion for these two soil conditions was found to be almost identical during subsequent studies in a laboratory soil pan. Bulk samples of each soil were studied in a 2- by 2-ft soil pan that was bounded all around by an additional 1-ft border of soil. The pan was tilted to a 6-pct slope, the same steepness as the field plots, and simulated rainfall was applied using the same nozzles, spray cycle, and intensity used on the field plots. The erosion from 5 inches of intense rainfall was 3.37 lb for the R-3 soil and 3.35 lb for R-4. Thus, these soils were essentially equal in their susceptability to rainfall detachment and interrill transport, so their major difference in erodibiilty was due to their susceptibility to detachment by runoff as indicated by the extent that they rilled.

Another rainulator study, on Miami silt loam, indicated the influence of rill frequency on erosion. Based on the data from four plots as given in table 1, denser rilling resulted in greater erosion. Plot M-1, 12 ft wide and 35 ft long, was smooth tilled and tested in this condition. Plot M-2 of the same size was also smooth tilled, but a main rill was formed down its center with a herringbone system of side rills leading into it at 2-ft intervals. Plots M-3 and M-4 were each 6 ft wide, and each had a main rill down its center with side rills draining into it in a herringbone pattern similar to M-2. A series of identical

TABLE 1.—*Effect of rill frequency on soil erosion*[1]

Plot	Downslope rills per 12 ft of width	Soil loss per 12 ft of width (lb)
M-1 (random rills)	3–5	686
M-3 (herringbone rills)	2	622
M-4 (herringbone rills)	2	609
M-2 (herringbone rills)	1	496

[1] Conditions: Soil—Miami silt loam. Slope steepness—6 pct. Slope length—35 ft. Rain—5 inches.

rainstorms totaling 5 inches was applied to all plots. Unrilled plot M-1 developed 3 to 5 (depending on the location) downslope rills, or an average of one rill per approximately 3 ft of width. Plots M-3 and M-4 each had one downslope rill per 6 ft, and plot M-2 had one rill per 12 ft. The plot with several rills had nearly 40 pct more soil loss than the one with only one rill. Results similar to those in table 1 were obtained in a similar study on an erodible Russell silt loam. (Soils that do not rill readily may not follow this trend, since broader distribution of flow may reduce their total erosion.)

Influence of Slope Length

Slope length affects erosion because runoff increases with distance from the top of the slope. The increased flow will increase rill erosion with distance downslope, but erosion from successive interrill areas should not be influenced much by slope length. Hence, the rate at which total soil loss increases with distance depends on the relative contributions of interrill erosion and rill erosion. Total soil loss increases more rapidly with distance for a soil that is susceptible to rilling than for one that is not particularly susceptible.

Data from previously discussed plots R-3 and R-4 support this conclusion. Soil surface profiles were obtained before and after a series of simulated rainstorms. Elevations were taken at 1-inch intervals across these plots at successive 5-ft locations downslope using a "profilemeter" (*6*). Although variability of the data was great, trends of these measurements, as plotted in figure 1, suggest how erosion varied with slope length. On rill-susceptible plot R-3, the erosion loss at successive downslope sections increased rapidly with distance. However, soil losses at successive sections for rill-resistant plot R-4 changed little with slope length beyond the top 5 to 10 ft. Since the soil pan results showed that

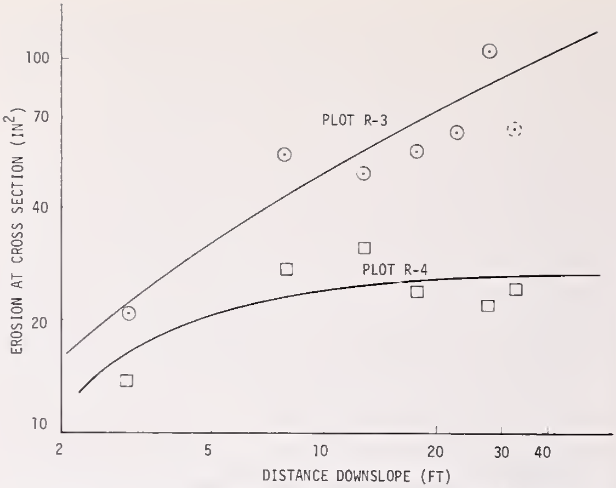

FIGURE 1.—Soil losses from rill-susceptible plot R-3 and rill-resistant plot R-4 as they varied with slope length. $L=35$ ft. $S=6$ pct. Rain totaled 5 inches at 2.5 inches/h.

interrill losses were similar on both plots, the rapid increase in soil loss with distance for plot R-3 was surely due to its increased rilling with distance downslope.

The two curves in figure 1 suggest how soil losses from conditions represented by plots R-3 and R-4 vary with slope length. Assuming that these curves can be reasonably extrapolated to a slope length of 50 ft, these data suggest that conditions like R-3 would lose less than 10 pct of their eroded soil from the top 10 ft of a 50-ft length of slope, whereas nearly 30 pct would be lost from the last 10-ft section. For soils like R-4 with little susceptibility to rilling, however, the total loss would be much lower and distribution would vary only slightly from 20 pct for any of the five 10-ft sections.

The profilemeter measurements were used to apportion the soil loss from plot R-3 between that occurring from the rilled portions and that from the interrill portions. Results are shown in figures 2 and 3*a*. Nearly all the loss near the top of this plot was from the interrill portion. Thereafter, rill losses increased rapidly with distance until they equaled the cross-sectional area of loss for the interrill portion at about 25 ft downslope. By this distance, the erosion on the interrill portions was essentially constant.

Although cross-sectional area of loss from rills and from interrill areas was equal at about 25 ft downslope, the cumulative volume of soil eroded from the rilled portions would not equal that from the interrill portions until about 45 ft

downslope (fig. 3*b*). In other words, the sediment load at about 45 ft would have been composed equally of soil originating from the rills and of soil from the interrill portions. Beyond that point, more than half the eroded soil would have been derived from rill portions. More studies on longer slopes are needed to better define curves of the type in figures 1, 2, and 3, and to help identify the sources of eroded soil beyond the range of the reported data.

The results in figure 1 show that the source of eroded soil and the influence of rilling were quite different for the R-4 soil than for the R-3 soil. For the relatively short slopes that were studied, R-4 had minor rill losses, and nearly all soil came from the interrill portions. On longer slopes, this soil would likely become susceptible to serious rilling also. Probably curves similar to those shown in figures 2 and 3 would eventually develop for R-4, but such curves would be greatly elongated along the "distance downslope" axis. Again, further studies to identify these differences are needed.

The influence of slope length, L, on the average erosion, A, per unit of area for a given slope is commonly expressed as $A \propto L^n$ (*19, 24*). Analyses of available data (*20*) showed that n may vary from 0 to 0.9.[6] Values near $n=0.5$ have been

[6] Soil loss may be expressed as all loss from a slope, G; as the loss averaged over the entire slope length, A_a; or as the loss at successive cross sections, A_x. The influence of slope length L, on each may be expressed as $G \propto L^{n_t}$, $A_a \propto L^{n_a}$, and $A_x \propto L^{n_x}$. The exponents, $n_a = n_x$, and $n_t = n_a + 1 = n_x + 1$, e.g. $A_a \propto L^{0.5}$ and $A_x \propto L^{0.5}$ when $G \propto L^{1.5}$.

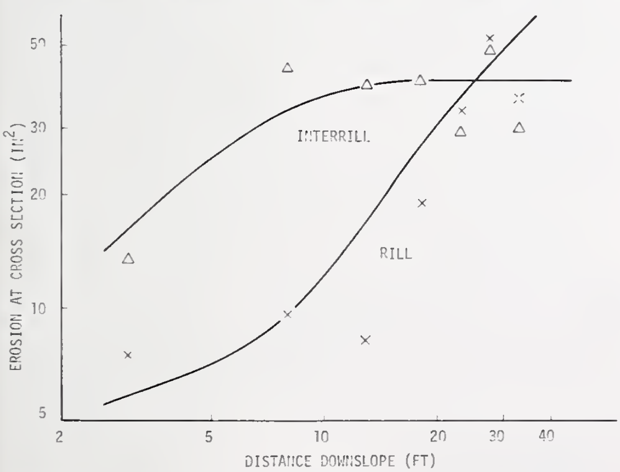

FIGURE 2.—Rill losses for plot R-3, as determined from microrelief data, and interrill losses, computed as difference between total R-3 erosion in figure 1 and rill losses.

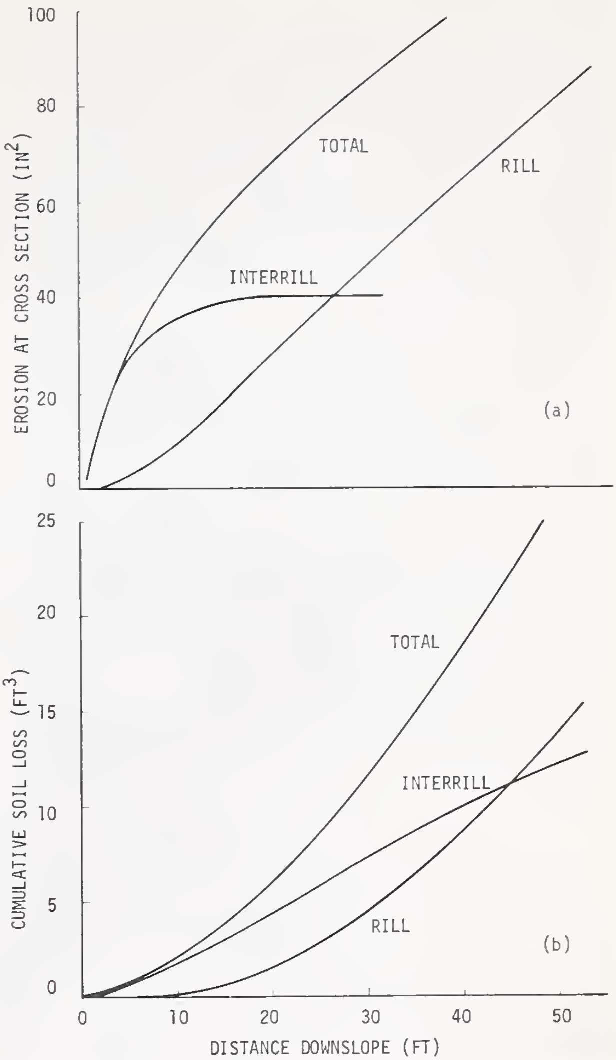

FIGURE 3.—Eroded soil apportioned between rill and interrill sources for rill-susceptible plot R-3.

used for most circumstances (*19*). Recent analytical studies strongly indicate that the value of this exponent depends on the relative susceptibility of different soils to rilling and the resulting ratio of rill erosion to interrill erosion (*4, 7*). For slopes where soil loss is primarily from rills, the exponent will approach 1, but it will approach zero where erosion is dominantly from the interrill portions. This trend is clearly supported by the data presented in figure 1, since the exponent n in the equation is the inclination of these curves.

Other data on soil loss at successive cross sections is scarce. Smith et al. (*15*) studied the erosion loss along five plots with lengths up to 270 ft. Measurements were made at downslope intervals of 10 ft during 1934 through 1939. Average

depths of erosion, except for the lower 20 or 30 ft where the plot-end sill affected them, are shown in figure 4. The relationship of best fit for the 270-ft plot data was reported as $y=0.016x^{0.57}$, where y was the average depth of soil loss in feet and x was slope distance in feet. However, the data from all plots as plotted in figure 4 suggest that a lower exponent, near 0.4, would fit these results better, but a curve of increasing gradient would fit them best.

Young and Mutchler (*23*) also measured the average loss at various intervals downslope for several slope shapes. Their results are plotted in figure 5. The slope of the log-log curve for the uniform slope data tends to increase with distance. This agrees with analytical results (*4, 7*) which showed that the slope n increases with increasing slope length because rill erosion increases faster than interrill erosion. Note that the results plotted in figures 4 and 5 lump rill and interrill erosion for these plots.

Influence of Slope Steepness

Land slope affects the source of eroded soil in several ways. Most obvious is the effect of the nominal steepness of an entire sloping area as commonly used in the universal soil loss equation (*19*) for measuring gross soil losses. In addition to such macroslope of an upland area, there are several microslope influences such as the relief between crop rows on the interrill slope, the meandering of rills and other flow channels as they move generally downslope but with some lateral components, and the meandering of flow around crop residues and other cover.

The universal soil loss equation relates the cross-sectional area of soil loss with slope steepness, S, as $A \propto 0.43+0.30S+0.043S^2$. This relationship is an average for many conditions and lumps the soil loss from rills with that from interrill areas. Solving this equation shows that erosion increases quite rapidly with slope steepness on the field length slopes for which it was developed. For instance, if the soil loss for a 2 pct slope is taken as 1.0, the loss for the same length, soil, etc., at 6 pct will be 3.1, the loss at 12 pct will be 8.5, and the loss at 20 pct will be 19.6.

Recent research at Lafayette has shown that

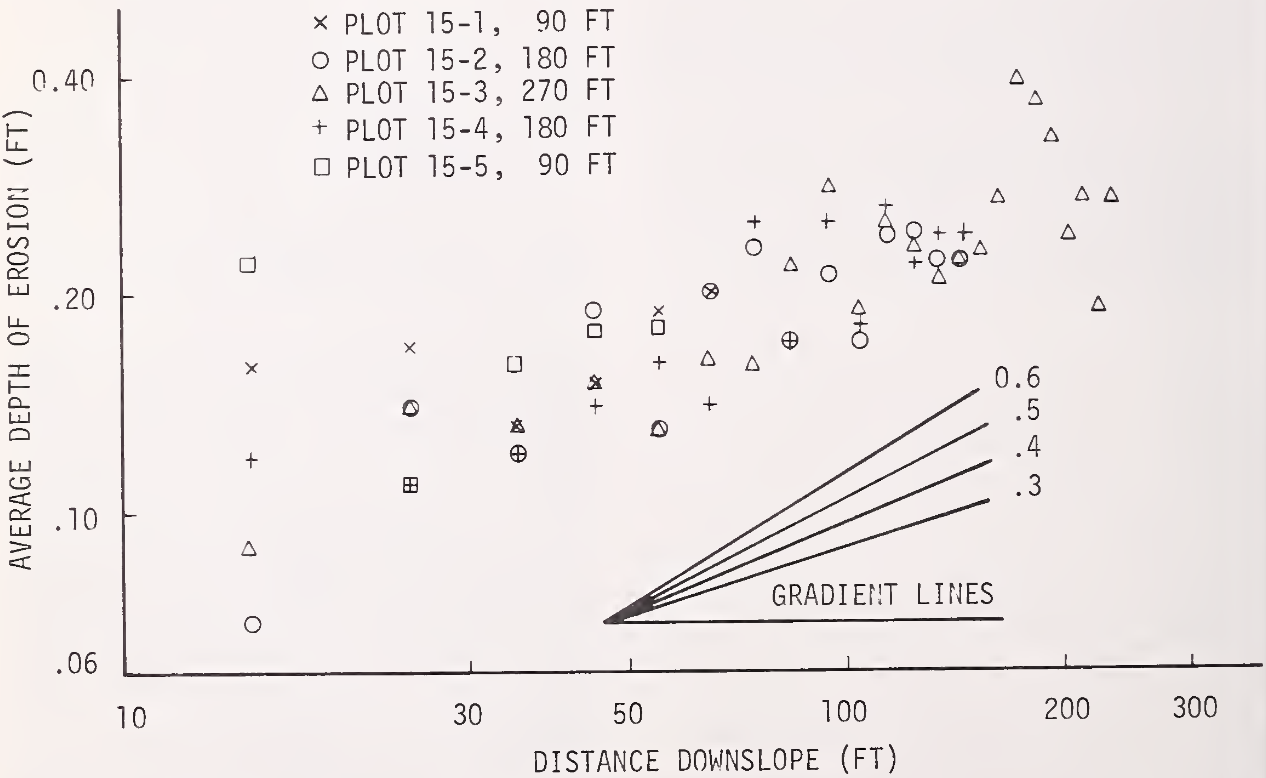

FIGURE 4.—Average depth of soil loss as affected by slope length for five plots under continuous corn, 1934–39. Shelby loam, $S=10$ pct, plot width 28 ft. Gradients shown suggest that curved line of increasing slope would give best fit. (Adapted from Smith et al., *15*.)

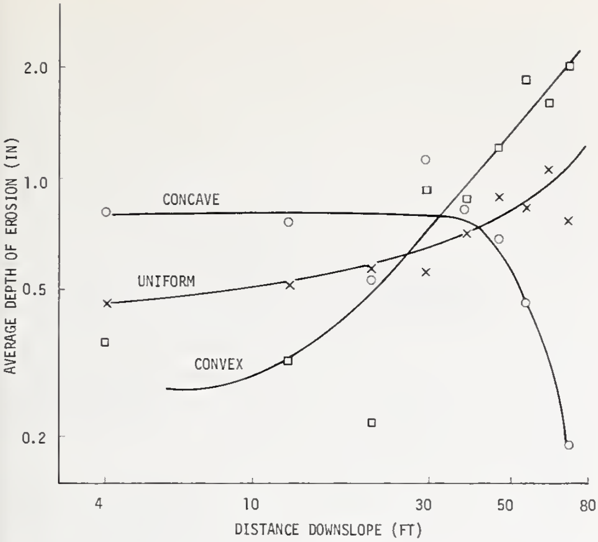

FIGURE 5.—Erosion of three mechanically shaped slopes from 5 inches of intense simulated rain. Crofton silt loam (deep loess soil) 13-1/3 ft wide, 9 pct average steepness (range of concave and convex 5 to 15 pct). (Adapted from Young and Mutchler, *23*.)

soil losses on short interrill areas do not follow this type of relationship. Instead, slope steepness has much less effect on interrill losses, as shown in figure 6. Considerable erosion occurs even when the soil surface is level, but the increase with slope steepness over a broad range of steepnesses is relatively small. Erosion only doubled for a steepness change from 2 to 20 pct as compared to the nearly 20-fold increase predicted above. Above 20 pct, the erosion rate tended to level off, as also shown by Foster and Martin (*8*) for some conditions. They found that, depending on bulk density, erosion on short slopes from 33 to 100 pct reached a maximum and then decreased as the slope steepened. A logical explanation is simply that the rate of soil detachment by rainfall changes slowly as slope steepness increases and that this largely governs the rate of soil loss. A slight increase in detachment rate probably occurs as the raindrops strike at a greater and greater angle, but this effect should not cause a major change in total splash detachment. Some particles and aggregates probably cannot be transported at small slope steepnesses, but most apparently can. The transport capacity of interrill flow is believed to increase rapidly as slope steepens; hence the availability of detached soil must be the primary limiting factor. Soil texture, aggregation, susceptibility to aggregate breakdown by raindrop impact, and other factors doubtless affect this relationship.

On silt loam soils and others where the relatively small change in interrill erosion with slope steepness expressed in figure 6 is appropriate, the amounts of soil eroded from the interrill areas and from the rills vary quite differently with slope steepness. Interrill erosion will be appreciable at even small steepnesses but may increase relatively little for steeper slopes. In contrast, the influence of steepness on losses from rills may be very great as the slope steepens. The net effect of losses from interrill areas and from the rill areas may be expected to approximate the relationship used in the universal soil loss equation.

The relatively small influence of slope steepness on short interrill areas was also hinted by Young and Mutchler (*22*). Using small tillage channels with furrow side angles of different steepnesses, they obtained results suggesting that a wide range of slope steepness affected ero-

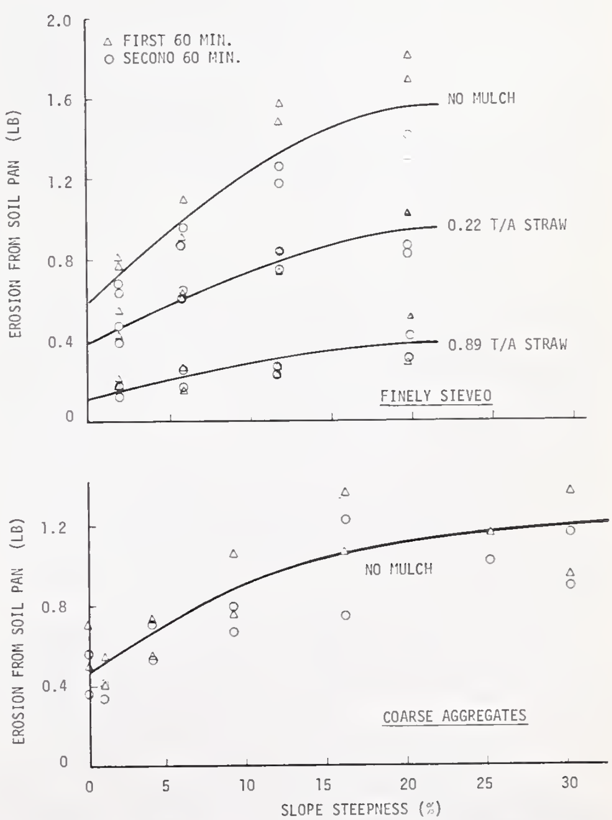

FIGURE 6.—Relation of soil loss to slope steepness on short interrill areas. Miami silt loam. Soil pan size 2 ft by 2 ft. Rain intensity 2.5 inches/h. (Data in top graph adapted from Lattanzi, *9*.)

sion very little for interrill areas varying from 4 to 16 inches in length. Although their results were not conclusive, they support the findings in the soil-pan studies discussed above.

No experimental data are available that describe rill erosion alone as a function of slope steepness. However, the tractive force, a measure of detachment potential of flow, increases with slope steepness, and thus rill erosion may be expected to increase with steepness.

Another very important effect of slope steepness is its influence on the transport capacity of the flow. Most sediment-transport relationships show transport capacity to change with some power greater than 2 of the slope of the energy gradeline. For unobstructed overland flow, this gradeline is approximately equal to the land slope. Thus, where land slope increases appreciably, transport capacity increases rapidly; conversely, where steepness decreases, transport capacity rapidly decreases. In the latter case, transport capacity may decrease to less than the sediment load and deposition may occur. Deposition often occurs at the toe of the slope or where obstructions such as vegetation, plant residues, and tillage channels slow or pond the flow and thus reduce the slope of the energy gradeline. The rate of deposition is apparently related to the difference between the sediment load and the transport capacity (*2, 4*).

Influence of Slope Shape

The shape of an irregular slope affects soil erosion through the influences of slope length and slope steepness and their interrelationships. Where both length and steepness are great, erosion may be expected to be great; where both are small, erosion will be small. Where slope steepness decreases as slope length increases, the effects will tend to offset each other. Such effects have been studied both analytically and experimentally.

The analytical results (*11–13*) are summarized in figure 7. Slopes of these sediment-load curves indicate the rate of erosion at any location. Erosion at successive points downslope increases gradually for uniform slopes. Losses for convex slopes are lesser near the top but increase very rapidly toward the end of the slope. For concave slopes, losses are greater near the top of the slope but decrease along the lower portions to the extent that deposition may occur. For com-

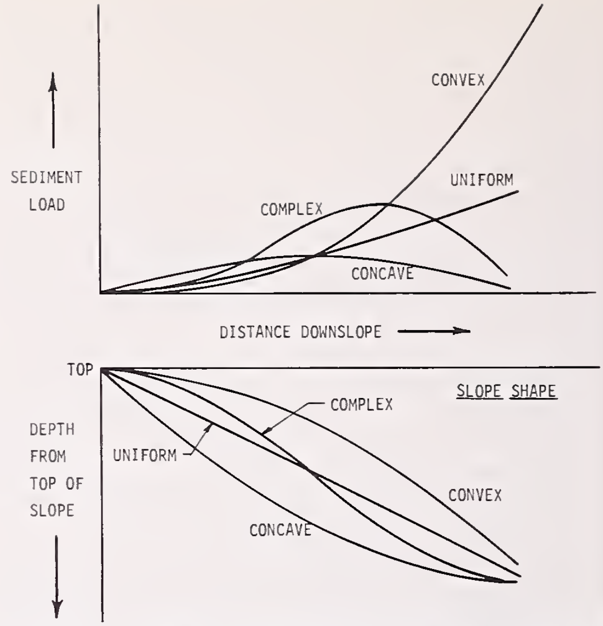

FIGURE 7.—Influence of slope shape on sediment load and rate of erosion. Steepness of sediment-load curves indicates rate of erosion, and negative slope indicates deposition.

plex slopes with their upper half convex and lower half concave, sediment load increases to a point approaching the toe of the slopes, and thereafter deposition may occur. The magnitude of the erosion and the location where deposition begins are functions of several factors including the relative susceptibility of the soil to rill and to interrill erosion, the curvature of the slope, and the runoff rate.

Experimental studies (*21, 23*) have generally supported the analytical conclusions. Data for carefully shaped slopes of uniform, convex, and concave shapes on a deep loess soil of uniform composition are shown in figure 5. Serious rilling occurred on these plots, but the extent of the interrill erosion was not determined.

Influence of Soil-Surface Canopy

A significant canopy over the soil surface may greatly reduce the total soil loss and also increase the percentage coming from the rilled portions as compared to that from the unrilled portions. Several soils were studied in the field and in the 2-ft-square laboratory soil pan to determine the effect of intercepting raindrops before they could strike the soil surface. Three layers of window screens were suspended several inches above the soil surface which had just received 5 inches of intense rain. The screen reduced erosion on

the field plots to less than 25 pct the erosion without screens. The reduction was generally much greater on the soil pan where the loss was only about 10 pct the loss from uncovered soil. Sample data from fallow, smooth-tilled soils for two rainfall intensities are given in table 2.

The field plots were approximately 100 times the area of the lab pans. Thus, table 2 indicates that about half the loss from the field plots came from the interrill areas when exposed to raindrop impact, but only a fourth of the loss was from the interrill areas when covered with a screen canopy. This relation held at both 2½- and 5-inch/h intensities. Since rill plus interrill erosion for the screen-covered plots was only half that attributed to rill erosion alone on the exposed plots, the screen canopy reduced rill erosion also. Whereas the screens reduced interrill erosion on the field plots by about 90 pct, the rill reduction was apparently around 60 pct.

The data in table 2 also show that increasing the rainfall intensity from 2.5 to 5.0 inches/h had about the same percentage effect on erosion for both the field plots and the lab pan. However, the intensity effect was greater without screen (erosion increased about 2.5 times) than with screen (erosion increased 2.0 to 2.3 times) for both the plots and the pan. Since the runoff rate from the 5-inch/h rain intensity was greater than twice that from the 2.5-inch/h intensity (assuming a significant infiltration rate), the increase in erosion due to intensity effect was little more than directly related to the increase in runoff.

Influence of Breakdown in Erosion Resistance

Recent studies have shown that once sloping land succumbs to severe erosion, a factor such as slope length may have a much greater influence on the erosion rate. Results indicate that such a "breakdown" starts when rapid rill development begins and progresses rapidly as the erosion hazard increases.

In one study (*10*), a series of intense simulated rainstorms applied on 35-ft plots was followed by additions of inflow to the upper ends of the plots. Inflow rates were increased in steps until the runoff rate was equivalent to 2 inches/h from a slope length of approximately 150 ft. Some treatments broke down from rainfall alone on the 35-ft lengths. Others did not break down

TABLE 2.—*Influence of screen canopy on erosion from field plots and soil pans*

Soil	Rain intensity (inches/h)	Erosion rate[1] (lb/min) Lab pan Without screen	Lab pan With screen	Field plot Without screen	Field plot With screen
Miami					
(M-1)	2½	0.0315	0.0042	6.6	1.8
Do	5	.0785	.0088	17.0	3.3
Russell					
(R-3)	2½	.0331	.0040	6.6	1.5
Do	5	.0842	.0095	18.5	3.7

[1] During 15-min runs following 5 inches of intense rain.

even with inflow sufficient to simulate a 150-ft slope length. However, several treatments that were not seriously erodible at 35 ft subsequently broke down and were eroding at very rapid rates by the time the extreme condition was reached. Examples of these three erodibility results are shown in figure 8. Note that erosion rate before breakdown is a quite different function of slope length than after breakdown. For such conditions, the location where eroded soil originates along a slope would be quite different than that predicted by a single straight line drawn through either of the center two sets of data in figure 8 or by a slope-length formula, $E \propto L^n$, fitted to such logarithmically transformed data.

In another study, rill erosion at successive cross sections was investigated on several soils. Rills were preformed with semicircular cross sections, 3 inches wide and 1-1/2 inches deep. They were constructed directly downslope with inflow from a herringbone system of side rills at 2-ft intervals. A "rillmeter" (*6*) was used to obtain elevations at 1/4-inch intervals across the rills prior to each of several successive rainstorms. Sample data for losses from 5 inches of rain are given in figure 9. Note that rill erosion changed relatively slowly with the slope length until serious erosion began, and thereafter it increased more rapidly. Again, the slope-trend changed near the locations where severe rill erosion began.

Influence of Soil Source on Particle-Size Characteristics

The location where eroded soil originates and the erosive agents that are dominant in detaching and transporting it can significantly affect the particle-size characteristics of the resulting

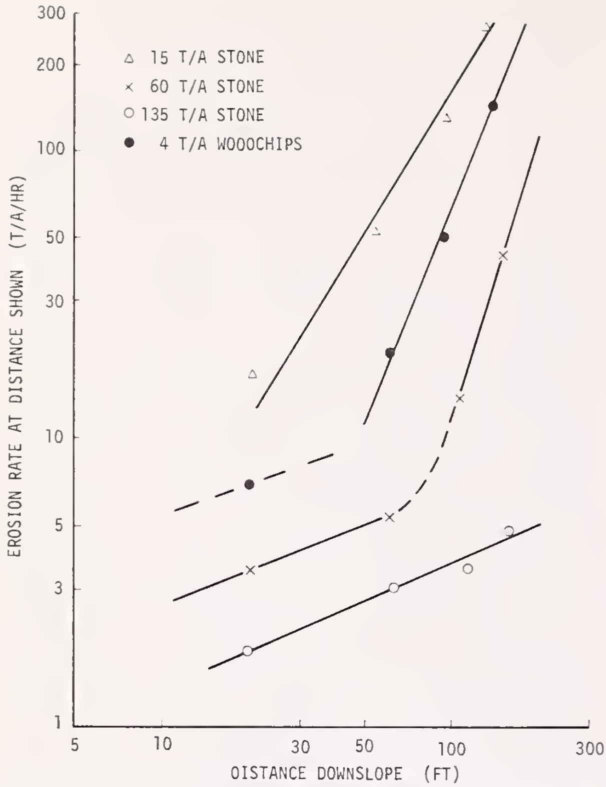

FIGURE 8.—Effect of slope length on soil erosion as influenced by "breakdown" due to severe rilling. Wingate subsoil, $S=20$ pct.

sediment. For cohesive soils, eroded material consists mainly of soil aggregates (*16, 17*). Aggregates apparently behave similarly to noncohesive particles during transport and deposition (*5, 7*), so their size and density must be considered in sediment-transport analyses. The size distribution of both aggregates and primary particles may differ from that of the original soil (*17*) and may change with storm duration (*16*). Raindrop impact tends to break soil into smaller aggregates, primary particles, or both, and rain effects are generally much greater on exposed interrill areas than within the rills.

The range in sizes and densities of detached soil material that is available for transport may result in selective erosion. Such selectivity was illustrated by textural differences of the runoff sediment from plots R-3 and R-4. Sediment sizes for samples collected at various times during a simulated rainstorm are plotted in figure 10. Sediment from R-3, characterized by severe rilling, approached the textural composition of the original soil as the storm progressed. However, the sediment texture of plot R-4, for which sediment from interrill areas dominated, differed appreciably from that of the original soil during the entire storm. The finer silt and clay fractions were higher, while the sand fraction was much lower. A logical conclusion is that interrill flow was unable to transport some of the larger detached soil particles, so greater percentages of finer sizes were eroded from the interrill areas of both plots. On plot R-4, where interrill areas were the dominant source, this resulted in eroded material of finer texture than the original soil. However, on plot R-3, where massive rilling was also a major source of eroded soil, size selectivity on the interrill portions was masked by the much less-selective rill erosion.

Particle and aggregate size selectivity may also result from deposition of part of the sediment load. Deposition may occur when runoff velocity is reduced by vegetation, mulch, or decreased slope steepness, so that the coarser and denser materials can no longer be transported. Smaller particles and aggregates will then be a larger percentage of the remaining sediment load. Young and Mutchler (*21*) found that the size distribution of primary particles from a concave slope was much finer than for the original soil, apparently largely because of deposition of larger aggregates and sand particles along the flatter portion near the toe of this concave slope.

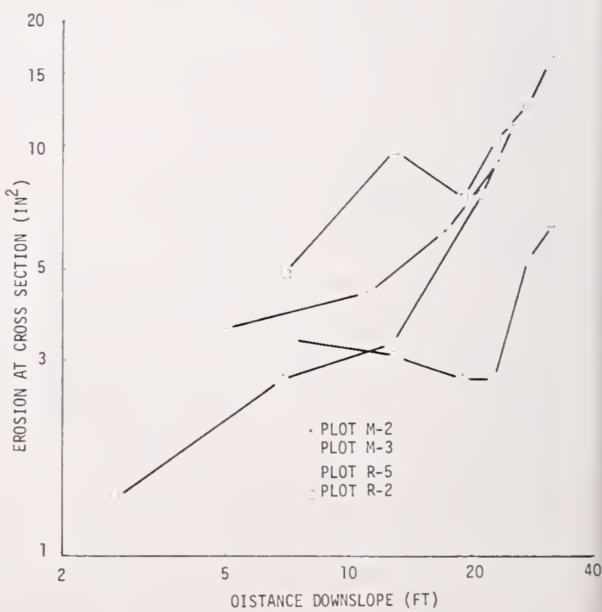

FIGURE 9.—Rill erosion in preformed, downslope rills as affected by slope length. Rainfall totaled 5 inches at 2.5 inches/h, $S=6$ pct.

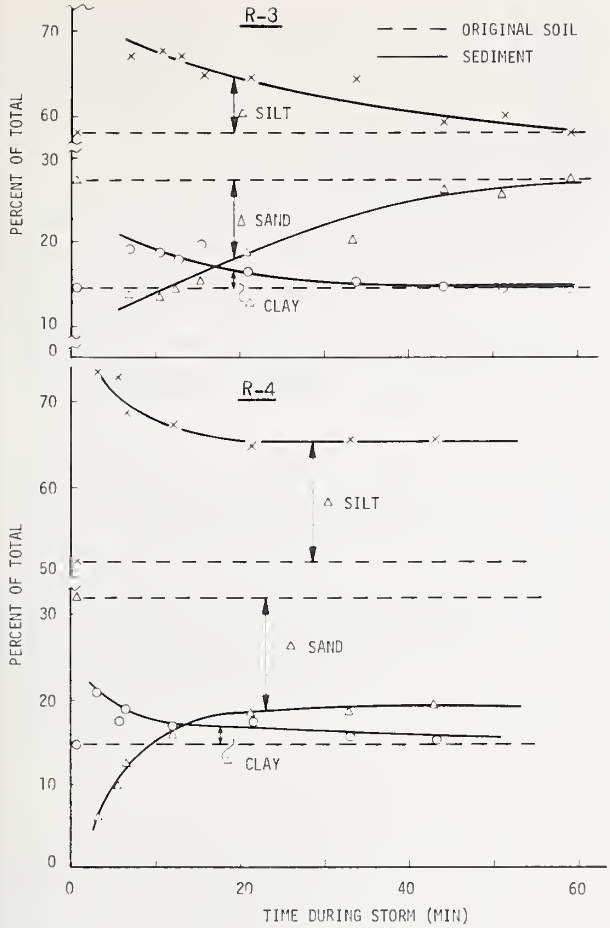

FIGURE 10.—Textural differences between eroded sediment and original soil for rill-susceptible plot R-3 and rill-resistant plot R-4 during first 60 min of rain.

The original soil was 22 pct clay, 29 pct silt, and 49 pct sand, but the concave-slope sediment was composed of 39 pct clay, 37 pct silt, and 24 pct sand during the first hour of rainfall. On uniform and convex slopes, where deposition was minor, the sediment size distribution was nearer the original soil: 31, 35, and 34 pct; and 31, 30, and 39 pct, respectively Possibly most of the latter selectivity was due to selective erosion on interrill areas, as discussed earlier.

Sediment Source as a Design Consideration

A land-management planner may need to satisfy various design criteria when developing erosion-control practices. Limitations may be based on the tolerable level of soil loss from land involved, the quantity of soil acceptable in streams and lakes below the sediment source, the physical, chemical and biological quality of eroded sediment, or combinations of these criteria.

Soil-loss tolerances have been based predominantly on the quantity of soil eroded from an upland area averaged over the entire area. Little attention has been given to limiting the soil-loss rate on each portion of a sloping area to prevent serious degradation. By learning more about the source of eroded soil all over a sloping area, prevention of excessive losses at all points can be a design consideration.

To develop designs that limit downstream sediment loads to acceptable amounts, practices that encourage deposition of soil eroded from upland areas before it reaches an established watercourse may have a significant effect. The extent of such deposition often depends on sediment characteristics as they are influenced by the sediment source. Failure to consider this effect has often explained much of the difference between the erosion predicted by the universal soil loss equation and the actual delivery to a downstream point. Furthermore, knowledge of the sediment characteristics that influence their tendency to settle out in streams and reservoirs may also be an important consideration. Again, better understanding of the source of the eroded sediment provides needed information for such considerations.

The chemical and biological pollutants that are carried by eroded soil are receiving more and more attention. The very fine colloidal fraction, consisting of clay particles plus organic and inorganic amorphous constituents, is usually the carrier of soilborne pollutants and nutrients (*1*, *14*). Thus, the portion of the sediment that is this fine fraction and the source from which it came is an important consideration in assessing the sediment's pollution potential. Also, material eroded from the soil surface, as is common from the interrill portions, may have a quite different concentration of pollutants than that eroded from an inch or more beneath the surface in the rilled portions. Similarly, soil eroded from one part of an upland slope may differ in chemical composition from that eroded from another part. Thus, when sediment characteristics are important in design, the source from which eroded soil originated must again be a consideration.

Erosion-control designs based primarily on the quantity of soil loss will continue to be important from the viewpoints of land farmability, stream and reservoir sedimentation, and similar considerations. However, additional emphasis on

reducing the loss of the very fine soil fraction appears to merit increased effort. The fine fraction is of greatest importance in soil fertility, water-holding capacity, and physical structure; it is the most difficult to remove by settling processes in water turbidity treatment; it carries the bulk of the soilborne chemical and biological pollutants; and conservation practices that control its loss certainly will reduce the loss of larger soil fractions and the total soil loss. On land where a significant portion of the eroded sediment comes from interrill erosion, minimization of raindrop impact effects will reduce the production of fine sediment. Also, reduction of raindrop effects is very important when a pollutant is concentrated at the soil surface. Plant canopies, plant residues, and other surface mulches are particularly effective in reducing raindrop impact. However, the contribution of fine sediment from rill erosion must not be overlooked. The percentage of fine particles in rill-eroded sediment may be smaller, but where rill erosion is dominant, its large volume of sediment production will also produce much fine material.

SUMMARY

Knowledge of the source of eroded soil can be very helpful in determining its physical, chemical, and biological characteristics. Such characteristics are of great importance in assessing the pollution potential of eroded material and in developing effective erosion-control practices. Recent research has helped explain how sediment source is affected by soil rilling, slope length, slope steepness, surface cover, and other factors. Division of the source between that from interrill areas and that from rill areas provides an approach that is very useful, analytically and experimentally. The significance of each of the above factors on rill and interrill erosion was discussed to the extent that data were available. The results show how such information can be used to better describe the process of soil erosion by water.

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MATHEMATICAL SIMULATION OF UPLAND EROSION BY FUNDAMENTAL EROSION MECHANICS[1]

By G. R. Foster[2] and L. D. Meyer[3]

Sediment load and erosion (or deposition) rate predictions are highly beneficial as a design tool in developing plans to control sediment loss and erosion damage on upland areas. Although several types of prediction techniques are potentially useful for this purpose, the discussion herein will be limited to deterministic formulations. The approach is based on physical principles of hydrology, hydraulics, sediment transport, and erosion mechanics. The purpose of the simulation is to predict sediment loads and erosion or deposition rates for all locations within an upland area and for all times during an erosion event. In addition to providing estimates of sediment yield, this comprehensiveness provides information that can be used in controlling local erosion hazards within the upland area. Otherwise, such hazards could not be considered in the design analysis.

For our purposes, any area within a watershed where runoff would be considered overland flow in a hydrologic analysis is an upland area. As figure 1 illustrates, both hillsides and bottom lands are included. Consequently, the deposition process that will be considered is that which often occurs when overland flow reaches the bottom lands, carrying eroded sediment from the hillsides.

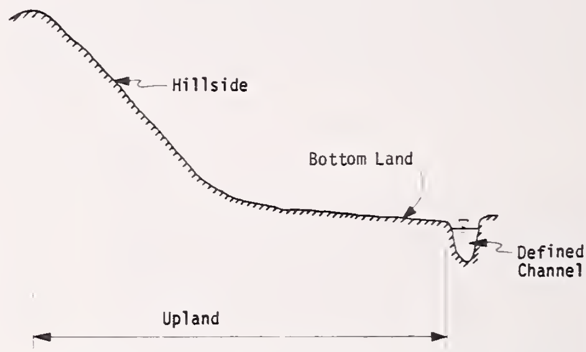

FIGURE 1.—Definition sketch of an upland area.

CONCEPTUAL CONSIDERATIONS

The erosion process is divided into interrill erosion and rill erosion according to source of the eroded sediment (*19*).[4] In general, runoff on erodible soil surfaces concentrates in many small, definable flow concentrations (*6*). Erosion occurring in these channels (rills) is defined as rill erosion, while erosion occurring on the areas between the rills is defined as interrill erosion. This separation is comparable to dividing the runoff process for a watershed into the overland-flow and channel-flow phases.

The mechanics of soil erosion follows from the definition that erosion is a process of detachment and transportation of soil material by erosive agents (*4*). For water erosion, these agents are rainfall and runoff. Based on this definition, the mechanics of erosion is composed of four subprocesses: detachment by rainfall, transport by rainfall, detachment by runoff, and transport by runoff. Although not all of the subprocesses occur on all source areas, each has its part in the total erosion process.

[1] Cooperative research of the Agricultural Research Service, U.S. Department of Agriculture, and the Purdue Agricultural Experiment Station. Purdue Journal Paper No. 4948.

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[4] Italic numbers in parentheses refer to items in "Literature Cited" preceding the appendix to this paper.

BASIC EQUATIONS[5]

The basic governing equation of the erosion process is the equation of continuity for sediment transport (*8*):

$$\partial G/\partial x = D_r + D_i, \qquad (1)$$

where G=sediment load (weight/time/unit of cross-section width, including total interrill and rill widths),
x=distance downslope,
D_r=detachment (or deposition) rate of rill erosion (weight/time/unit of total area, including rill and interrill areas),
and D_i=delivery rate of particles detached by interrill erosion to rill flow (weight/time/unit of total area).

Equation 1 is a mathematical description of the conceptual model of Meyer and Wischmeier (*22*), which is shown in figure 2. As presented by figure 2, the various processes do not interact other than in the manner indicated by equation 1. For example, if detachment is the limiting factor, the rate of detachment by flow is not a function of sediment load. However, erosion tests on beds of cohesionless particles showed that detachment by flow is a function of sediment load (*21, 37*). Degradation by streamflow below dams is also indicative of this interaction. A conceptual explanation as given by figure 3 is discussed by Foster and Meyer (*8*). Equation 2 expresses this concept in equation form.

$$D_r/D_c + G/T_c = 1 \qquad (2)$$

where D_c=the detachment capacity of the rill flow,
and T_c=the transport capacity of the rill flow.

Equation 2 has not been experimentally verified and should be regarded as a first approximation of the concept.

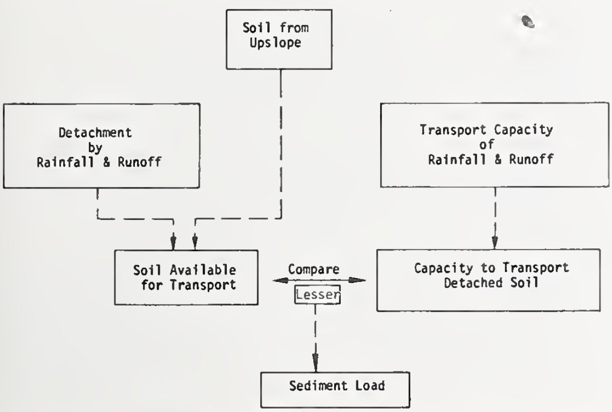

FIGURE 2.—Conceptual model used by Meyer and Wischmeier (*5*) to simulate the soil erosion process.

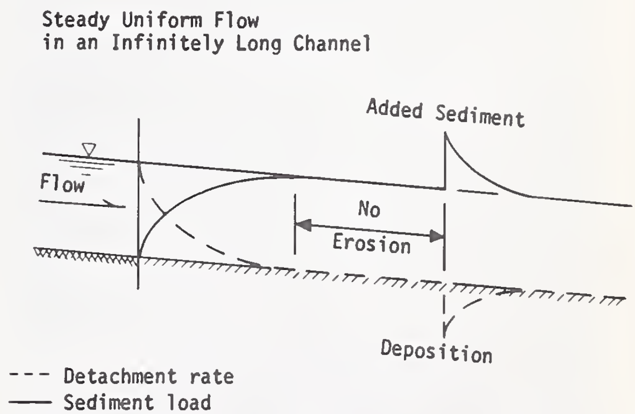

FIGURE 3.—Flow detachment-sediment load interaction.

MECHANICS OF THE SUBPROCESSES

The terms D_c, T_c, and D_i are independent variables defined by rainfall and runoff characteristics and by soil properties. The two unknowns in equation 1 and 2 are D_r, the detachment rate by the flow in the rills; and G, the sediment load.

Hydrology

A hydrologic consideration is basic in an erosion simulation because rainfall and runoff provide the energy required to detach and transport soil particles. For this discussion, the important rainfall characteristics are assumed either to be known or to be available from stochastic generation.

Runoff characteristics can be defined with a kinematic overland flow model (*2, 7, 26, 44*). Although this type of model assumes that the flow depth is uniformly distributed across the surface, the effect of flow concentration into rills on the discharge hydrograph is considered by the hydraulic roughness parameter of the model. The model provides velocity, flow-depth, and dis-

[5] A complete list of mathematical symbols and their definitions is given in the appendix to this paper.

charge data that are required as inputs for the erosion simulation. It normally includes parameters for retention storage, infiltration, and hydraulic roughness that must be selected without the benefits of a previous runoff record.

Huggins and Monke (*15*), in an analysis of small-watershed runoff composed primarily of overland flow, found that for agricultural conditions the infiltration, retention storage, and roughness parameters ranked in importance in the order listed. The infiltration function can be described by any of several well-known infiltration equations including the Green-Ampt, Holtan, Philip, and Horton equations (*32*). The one selected depends on such factors as convenience, capability for predicting infiltration recovery, and availability of values for the equation's parameters. For a given soil type, two factors seem to be highly important: antecedent moisture content and the presence of an impeding layer either at the soil surface or within the soil profile.

Retention storage is greatly influenced by the surface microrelief and by whether or not the rill pattern has formed. Contour tillage or tillage that leaves large soil aggregates produces greater retention storage. Retention storage will be greater for a storm occurring on a freshly tilled soil than for storms occurring after rills have formed. For tilled soil with newly planted corn, Huggins and Monke (*15*) found retention storage values of approximately 0.13 inch while Foster (*5*) found values of approximately 0.04 inch for eroded fallow surfaces. Close-growing vegetation does not necessarily increase retention storage where the microrelief of the soil surface is relatively smooth at the time of seeding. Huggins and Monke found retention storage values for growing timothy and wheat near those for eroded fallow.

Values for hydraulic roughness cannot be based on qualitative descriptions of the soil surface, such as rough fallow (*7*). However, Foster (*6*) found a relationship whereby the Darcy-Weisbach coefficient of friction varied with the —2.8 power of the soil erodibility factor of the universal soil loss equation (*43*). This relationship applies to eroded fallow conditions where the rill pattern has formed. Typical friction-factor values ranged approximately from 0.1 to 4.0 for moderately erodible soils on 35-ft erosion plots. Little is known about changes in the roughness factor while the rill pattern develops.

Interrill Erosion

Raindrop impact is a dominant factor in the detachment of soil particles on interrill areas. Raindrop impact and the thin sheet flow combine to transport these detached soil particles to the concentrated-flow channels. Conceptual models such as Rowlison and Martin's (*31*) are useful for understanding the interrill erosion process.

Detachment on interrill areas by flow will be neglected since the flow's shear stress is small because of the small depths and flow rates which occur on interrill areas. Furthermore, studies where screen wire was placed over soil pans to dissipate raindrop impact energy showed that interrill flow alone can detach only a small percentage of the particles as compared with raindrop impact (*19, 25*). For slopes less than approximately 4:1, the rate of detachment by raindrop impact is probably not strongly influenced by slope steepness (*19*). However, for slopes steeper than 3:1, Foster and Martin (*11*) found that depending on the soil's bulk density, detachment rate by raindrop impact reached a maximum and decreased with increases in slope steepness. The shape of this function is represented by the *A'BC* portion of the curve in figure 4.

For small steepnesses, conceptual models (*22, 31*) suggest that transport capacity on interrill areas could be less than the availability of detached materials. The transport-capacity relationship is represented by the *ABC'* curve in figure 4. This curve has a transport-capacity intercept greater than zero for a flat slope because even at zero slope, flow has the capacity to transport some particles. The limiting component, i.e., the lesser of curves *A'BC* or *ABC'* is the delivery rate D_i of particles detached on interrill areas

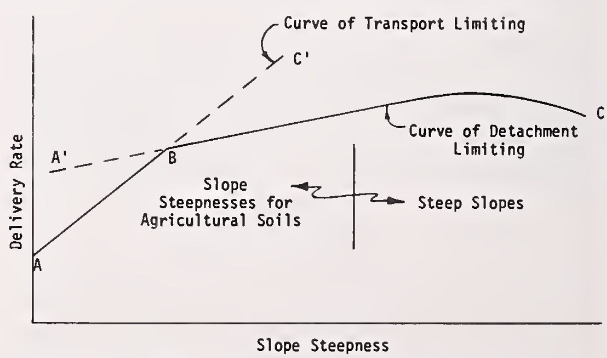

FIGURE 4.—Conceptual model of the delivery rate of detached particles from interrill areas to rill flow.

to the rills. In actuality (*19*), these curves will not necessarily be so well defined. Transport capacity probably does not become limiting abruptly. Instead, until the steepness at point B in figure 4 is reached, probably neither detachment nor transport capacity is entirely limiting. At lesser slopes, detachment dislodges particles larger than can be transported at those steepnesses. Thus, segregation of particle sizes occurs which tends to smooth the curves shown in figure 4. These effects may have been present in an experiment by Moldenhauer[6] in which detached particles were added to a small soil pan on a 9-pct slope, which was exposed to simulated rainfall. However, he found that under those conditions more particles could be transported than were being detached, which demonstrates that interrill transport capacity can exceed interrill detachment rate. Since present information is insufficient to better define the process, figure 4 is proposed as a model of interrill erosion. The curves in figure 4 can shift and vary depending on factors including rainfall characteristics and soil properties.

Even for a constant rainfall intensity, the rate of particle detachment by raindrop impact is a time-dependent function. In some cases the rate increases rapidly in the beginning, reaches a peak, and then decays exponentially to a steady-state rate (*23*), while in others it may actually increase with time. Unfortunately, in most studies of the effect of rainfall characteristics on raindrop-impact detachment, the time-dependency effect of changing soil characteristics has been lumped with the rainfall parameters.

Generally, total interrill soil loss for a storm has been expressed as a function of the total energy of the storm. Free (*12*) found that for a given storm the total detachment A_i by rainfall could be expressed as $A_i = K_F E_{ke} i_{30}$, where A_i is in units of weight/unit area, E_{ke} is the total energy of the storm (force-distance/unit area), i_{30} is the maximum 30-min intensity (inches/hour), and K_F is a coefficient including the effect of soil properties. For a constant rainfall intensity, $E_{ke} = (e)(i)(t)$, where e is kinetic energy per unit of rainfall, $i = i_{30}$, and t=time. Wischmeier and Smith (*42*) found that for natural rainfall, $e = 916 + 331 \log_{10} i$. For intensities between 0.5 and 10 inches/h, this expression can be approximated by $e = C_i i^{0.14}$. Therefore, for a storm of constant intensity, $A_i = C_i K_F i^{2.14} t$. By differentiation with respect to time, $D_i = C_i K_F i^{2.14}$, which indicates no time dependency for D_i.

Bubenzer and Jones (*1*) found that $A_i = K_{BJ} i^{0.4} (E_{ke})^{1.3}$. By following the above procedure, D_i is given as $1.3 K_{BJ} i^{1.88} t^{0.3}$ which does include a time factor. Here, the time factor is assumed to be due to the initial wetting and progressive erosion of the soil. The raindrop mechanics of the process are explained by the $i^{1.88}$ term. A plot of Moldenhauer and Long's data (*24*) indicates that $D_i \propto i^{2.4}$ for five Iowa soils in their study. Based on these results, an assumption of $D_i \propto i^2$ is reasonable and agrees with the suggestion of Meyer and Wischmeier (*22*).

The soil characteristics affecting raindrop-impact detachment are difficult to quantify because they vary with time. They are affected by wetting of the soil, erosion of particles, and formation of a surface seal. Moldenhauer and Koswara's (*23*) experimental result illustrates the time effect. Efforts to evaluate it or even steady-state rates of detachment with respect to soil properties are scarce. Bubenzer and Jones (*1*), using only one type of clay, related total soil detachment to percent clay. In the absence of a tested parameter, the soil erodibility factor (*41*) in the universal soil loss equation may be the best available indicator of the relationship between raindrop impact and the soil properties controlling detachability.

The transport capacity of interrill flow is a function of several factors that include runoff rate, slope steepness, roughness of the surface, transportability of detached soil particles, and effect of raindrop impact. Evidently, raindrop impact significantly increases the transport capacity of interrill flow. Interrill flow without impacting raindrops is probably able to transport only a small load (*30*). Direct splash of detached particles through the air to rills seems to be minor compared to soil transported by sheet flow (*19, 25*). The impact of drops near detached particles lifts them into the flow and then the flow's drag force moves the particles a distance downslope before they settle back to the soil surface. The relationship between the increase in transport capacity of thin sheet flow due to raindrop impact and rainfall parameters is not

[6] Private communication from W. C. Moldenhauer, Morris, Minn.

known, but likely the capacity increases as some function of rain intensity.

When the effect of raindrop impact is not considered, interrill transport capacity may be expressed as (*8*):

$$T_{ci}=C_{si}(S_i+C_{so})\,q_{oi}=C_{si}(S_i+C_{so})\,\sigma L_i, \quad (3)$$

where T_{ci}=interrill transport capacity,

C_{si}=a coefficient expressing the transportability of the soil detached by raindrop impact on the interrill areas,

C_{so}=a factor accounting for the transport capacity of interrill flow at zero slope,

L_i=slope length of the interrill flow,

S_i=slope steepness of the interrill area,

q_{oi}=discharge per unit width at L_i

and σ=excess rainfall rate (rainfall rate-infiltration rate).

As a first approximation, the effect of raindrop impact on T_{ci} may be added by assuming it to be directly proportional to rainfall intensity. Equation 3 becomes:

$$T_{ci}=C_{si}(S_i+C_{so})\,\sigma L_i(\Phi i), \quad (4)$$

where Φ=a constant.

Equation 4 shows that the major factors affecting interrill transport capacity include rill density as it affects L_i, rainfall intensity represented by i and σ, microtopography by S, and transportability of the particles by C_{si}. For common soils, soil particles detached by raindrop impact are largely aggregates with specific gravities near 2.0 (*17*). Their diameters range from approximately 0.002 to 2.0 mm, with the majority being greater than 0.5 mm (*23*).

Rill Erosion

The two major subprocesses active in rill erosion are detachment by flow and transport by flow. The development of the rills themselves is a result of flow detachment. Rill flow transports flow-detached particles as well as those delivered to the rills from the interrill areas. If the quantity of particles available for transport exceeds the transport capacity, deposition occurs. Deposition is the negative of detachment.

Expressions for D_c and T_c in equation 2 will be developed in the following discussion to complete the analysis of the required inputs into equations 1 and 2. With relationships for D_c, T_c, and D_i, equations 1 and 2 can be solved for the unknowns D_r and G.

The detachment capacity of rill flow D_c describes the rate per unit of total area at which rill flow can erode particles from the soil mass at a location on the slope if there is no sediment load. Because the flow contains a sediment load the detachment rate is normally less than the detachment capacity. Some researchers (*31*) have neglected rill detachment from their consideration in developing an erosion model. If the shear stress is estimated by assuming sheet flow, its estimated value is quite small and suggests that overland flow has no capacity to erode. However, overland flow, concentrated in rills on 35-ft erosion plots, approached a 0.5-inch hydraulic radius in the rill for a 6-pct slope with a 2-inch/h runoff rate. This gives a shear stress of 0.16 lb/ft^2, which is comparable to that in a 4-ft-deep stream on a 0.0006 slope. Confusion also exists concerning the critical shear stress for soil. Values from 0.02 to 0.5 lb/ft^2 are reported in the literature (*13*). Based on data from agricultural soils, the critical shear stress is probably near 0.05 lb/ft^2. Since the flow's shear stress in the above example is about three times the critical value, rilling of unprotected slopes is likely.

Much of the published information concerning the erosion of cohesive soils is directed toward predicting the point of incipient motion. This is usually accomplished by comparing the flow's average shear stress to the critical shear stress of the soil. Therefore, much effort has been devoted to defining the critical tractive force τ_{cr} and relating it to various mechanical soil properties such as vane shear strength, plasticity index, and dispersion ratio. However, these properties have not been adequate to define critical tractive force (*14, 29*). Until a satisfactory method is developed, the relationship $\tau_{cr}=0.213/d_r^{0.63}$ (where d_r=dispersion ratio) by Smerdon and Beasley (*33*) seems best for agricultural soils.

The relation of flow variables to detachment capacity has received little study. Partheniades (*27*) found that the erosion rate depended strongly on the increase of the average bed shear past a threshold value. He derived a detachment capacity equation based on the assumption that the bed shear varied as a normal distribution

with time. For his series I test in the upper three-fourths range of shear stress, detachment rate varied with the average shear stress to the 1.9 power. A relationship of the type $D_c = C_\tau(\tau - \tau_{cr})^a$ is a possible expression for D_c. Because of the assumptions made in its derivation, the Yalin sediment transport equation (*45*) appears to be an equation for expressing detachment per unit area per unit time, provided an appropriate critical shear stress is used. If the bed shear stress is large compared to the critical shear stress, this equation reduces to an expression of detachment capacity as proportional to the 3/2 power of the tractive force. At present, the Yalin equation with the Smerdon-Beasley critical tractive force relationship appears to be useful for estimating D_c.

A transport capacity, T_c, is required to transport detached soil particles. The material available for transport is primarily made up of aggregates rather than primary particles (*35, 36*). Also, ponding of the flow produces rapid deposition. This led to the conclusion (*10*) that detached particles move primarily as bedload and thus the transport capacity of rill flow can be expressed by bedload formulas. Formulas that have been used include the Yalin (*10*) and the DuBoys (*46*). Other equations as well as the similitude results of Willis and Coleman (*38*) apparently can also be used.

The magnitudes of the flow variables at all locations along every rill must be known to apply these equations directly. These variables include the hydraulic radius, slope of the energy gradeline (normally taken equal to the land slope in the direction of flow), discharge, average velocity, roughness factor, and particle size. Unfortunately, little information concerning the frequency of rills or the cross-sectional geometry of the rills is available until after the rills have formed and measurements have been taken. Neither are values for hydraulic roughness available. However, provided the rill system can be defined, the latter problem can be overcome, as will be explained in a later section.

Sediment deposition is examined here as a subprocess separate from either detachment capacity or transport capacity, although it is related to both. Deposition on upland areas is a major reason why soil loss predictions with erosion equations, such as the universal soil loss equation (*34*), often do not agree with observed sediment yields. A delivery-ratio concept is often used with these equations to account for the deposition.

In terms of the mathematics of equations 1 and 2, deposition is the negative of detachment. It occurs because the sediment load of the flow exceeds the flow's transport capacity. This can happen where the transport capacity is reduced because of the flattening of the energy gradeline as flow reaches the bottom lands or enters ponded water. Flow through mulch or vegetation also has less transport capacity (*9*), which may produce deposition when mulch or vegetation lies downslope from bare soil.

Studies of the deposition process as it relates to upland areas are scarce. Partheniades (*28*) presented a summary of several basic studies in which he participated, but his results may not apply to upland erosion. A concentration of 10,000 to 20,000 p/m is the limiting point for his results whereas concentrations of 50,000 to 100,000 p/m are commonplace in upland erosion and sometimes reach several times that level. Also, his commercial kaolinitic clay apparently behaved differently than is common for the sediment in rill flow during deposition. When soil eroded from upland areas deposits, it seems to follow the deposition mechanics of noncohesive particles. Therefore, an expression similar to one developed by Einstein (*3*) may be used to approximate the rate of deposition:

$$D_d = C_d(T_c - G), \tag{5}$$

where D_d = deposition rate (negative detachment rate),

and C_d = a coefficient which is a function of sediment-fall velocity, water quality, and depth of flow.

Equation 5 is a rearrangement of equation 2, where $D_c = C_d T_c$. When T_c is evaluated for depositing flow, the broader and shallower flow that develops with progressing deposition must be considered.

Simulating Soil Loss From Erosion Plots

The principles discussed above were used to simulate steady-state soil loss from 35-ft erosion plots under simulated rainfall applied at 2-1/2 inches/h. Available data included estimates of d_r and D_i, microrelief profiles, and observed hydrographs. The Yalin equation was used to deter-

mine T_c at 1-ft intervals down the plot. A particle diameter of 0.05 mm and a specific gravity of 2.2 were used for the material eroded from both interrill areas and from the rills (*17, 23, 35, 36*). The detachment capacity was evaluated by the Yalin equation and the Smerdon-Beasley critical shear stress relationship.

The hydraulic radius of the flow in each rill at each location was determined by imposing the average overland flow depth onto the microrelief profile as shown in figure 5. The percent of the average depth allocated to each rill was equal to the percentage of the total upslope plot area that each rill drained. Since the rills were parallel with the slope, this percentage was easily determined. The microrelief profile at approximately 13 ft from the lower end of the 35-ft plot was taken as representative of the entire plot.

The average depth $\overline{y}$ at a location was evaluated from the uniform flow equation of

$$\overline{y}=[\sigma x/(8gS/f)^{1/2}]^{2/3}, \qquad (6)$$

where g=acceleration of gravity (32.2 ft/s²),
and f=Darcy-Weisbach coefficient of friction.

Values of f were obtained by fitting an overland flow hydrograph generated by a kinematic model to the observed runoff hydrograph from an eroded wet soil.

Erosion simulations made for several plots with steady runoff, using equations 1 and 2, produced the results given in table 1. The correspondence of the predicted and observed soil losses indicates the potential for such a type of mathematical simulation once the rill pattern has developed.

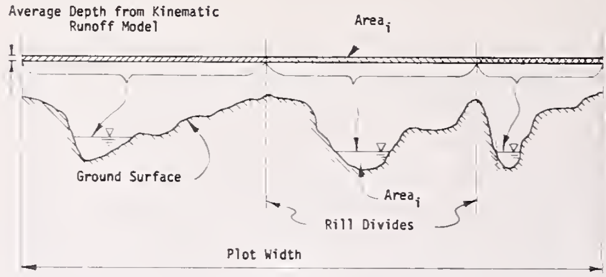

FIGURE 5.—Distribution of the average flow depth to the rills on an erosion plot.

TABLE 1.—*Comparison of soil loss prediction by simulation with observed steady state soil losses*[1]

Soil type	Plot width (ft)	Micro-relief[2]	Results (tons/ acre/h) Predicted	Observed
Russell silt loam	12	DUDS	11.7	7.8
Do	12	RP	12.1	11.5
Do	12	S,P	11.7	14.2
Miami silt loam	12	HPRP	15.0	14.7
Do	6	HPRP	18.8	17.6
Sylvan silt loam	6	HPRP	25.8	23.4
Russell silt loam	12	S,L	11.0	10.9
Do	12	HPRP	19.5	13.0

[1] Observed data from 35-ft erosion plots with 6-pct slope.

[2] The microrelief codes are DUDS—disked up-and-down slope; RP—rough plowed; S,P—smooth, packed with lawn roller; HPRP—herringbone preformed rill pattern; S,L—smooth, loose surface.

CLOSED-FORM EROSION EQUATIONS

Reduction of a complex model to equation form sometimes reveals characteristics of the model that otherwise would remain hidden in its complexity. Furthermore, the resulting equation(s) may be useful as a simplified design tool.

Closed-Form Equations Using Equation 2

Foster and Meyer (*8*) derived equations 7 and 8 as the solution to equations 1 and 2:

$$(D_r/D_{co})=\exp(-\alpha x_*)\int(dg_*/dx_*-\Theta)\exp(\alpha x_*)\,dx_*+C \qquad (7)$$

and

$$G/T_{co}=g_*-(D_r/D_{co}) \qquad (8)$$

Equations 7 and 8 are general erosion equations for any irregular slope shape, within the limitations of the assumptions of the derivation. A uniform slope through the end points of the irregular shape is a reference slope. The terms D_{co} and T_{co} are, respectively, the detachment capacity and transport capacity at the end of the reference slope. The other terms are defined as $x_*=x/L$, $\alpha=LD_{co}/T_{co}$, $\Theta=LD_i/T_{co}$, $g_*=T_c/T_{co}$ and C=constant of integration.

Several assumptions are necessary to obtain equations 7 and 8. Steady-state and a uniform rainfall excess are assumed. The Yalin equation is assumed to describe D_c and T_c, and with the assumption of large τ, $D_c=C_D\tau^{3/2}$ and $T_c=C_T\tau^{3/2}$. The coefficients C_D and C_T are taken as independent of slope steepness or distance along the

slope. As a result of this assumption, rill density is a function of only soil properties and the excess rainfall rate. The term D_c is expressed on a per-unit total area basis and T_c on a per-unit total width basis. The coefficients C_D and C_T account for the effects of concentrated flow on the average shear stress of the overland flow. The average shear stress is calculated from $\tau=\gamma\bar{y}S$ with equation 6 and a value for f that is both constant along the slope and independent of slope steepness. These assumptions give $D_c \propto f^{1/2}\sigma xS$ and $T_c \propto f^{1/2}\sigma xS$. Also, $g_*=D_c/D_{co}=T_c/T_{co}=x_*S_*$ where $S_*=S/S_o$ and S_o=the slope of the reference profile. If S is greater than the steepness at which raindrop impact detachment rate becomes limiting on the interrill areas (fig. 4) and its range is small, Θ may reasonably be assumed constant. If S is small or its range is large for a slope, then Θ becomes a function of S and may be written as $\Theta=\Theta_0 D_{i*}$ where Θ_0 is for the reference slope, $D_{i*}=D_i/D_{io}$, D_i is a function of S and D_{io} is the interrill delivery rate of detached particles for the reference slope.

Equation 7 can be integrated to obtain a closed-form erosion equation, provided g_* and Θ can be written as functions of x_* and a closed-form solution exists. Equation 7 can be numerically integrated when a closed-form solution does not exist or when g_* and Θ are given as a function of x_* in tabular form. Increments of $\Delta x_*=0.01$ are sufficiently small to obtain an accurate solution for the detaching state (i.e., $D_r>0$), but a $\Delta x_*=0.001$ is better for deposition predictions (i.e., $D_r<0$). At the x_* location where $D_*=0$, the process is in transition from a detachment to a deposition status or vice versa. A new C must be evaluated at this x_* because α takes on a new value due to a change in C_d in the equation $D_c=C_dT_c$. In a sense, this is a result of the flow being able to deposit sediment more easily than it can erode soil.

For the special case of a uniform slope, $\Theta=\Theta_0$, $g_*=x_*$, and equations 7 and 8 reduce to

$$D_*=(1-\Theta_0)[1-\exp(-\alpha x_*)] \qquad (9)$$

and $G_*=x_*-(1-\Theta_0)[1-\exp(-\alpha x_*)]/\alpha$, (10)

or in their general form to

$$D_*=(1-\Theta_0)[1+C\exp(-\alpha x_*)] \qquad (11)$$

and

$$G_*=x_*-D_*/\alpha, \qquad (12)$$

where $D_*=LD_r/D_{co}$
and $G_*=G/T_{co}$.

Values of α and Θ_0 were calculated by previously discussed techniques and were used to calculate values of G_* and G for several erosion plots. The results are shown in table 2. The distribution of G with distance as given by equation 10 is graphically compared with experimental data (*19, 47*) in figures 6, 7, and 8. Values for α and Θ_0 in figures 7 and 8 were calculated using the Yalin sediment-transport equation to estimate D_{co} and T_{co} as discussed previously. Since D_i was known from a laboratory study, values of α and Θ_0 were determined directly. For the Young and Mutchler data in figure 6, α and Θ_0 were estimated by comparing a description of their plot conditions and soil loss rates to those where α and Θ_0 were known. In contrast to the usually assumed linear relation on log-log scales, equation 10 plots curvilinearly, with slope a function of α, Θ_0, and x_*. Depending on these values, equation 10 may produce a convex, concave or S-shaped curve on a log-log scale. The equation for the slope of this type of plot for equation 10 was given by Foster and Meyer (*8*) as $n=x_*[1-(1-\Theta_0)\exp(-\alpha x_*)]/G_*$.

TABLE 2.—*Comparison of predictions by equation 10 with observed soil losses from 35-ft erosion plots under simulated rainfall*[1]

α	Θ_0	G_* at $x_*=1$	Interrill delivery rate, D_i (tons/acre/h)	Soil loss (tons/acre/h) Predicted	Soil loss (tons/acre/h) Observed
0.046	0.057	0.0784	10.0	13.7	11.5
.250	.029	.1409	7.7	37.2	29.0
.065	.043	.0734	7.7	12.3	10.9

[1] From Foster and Meyer (*8*).

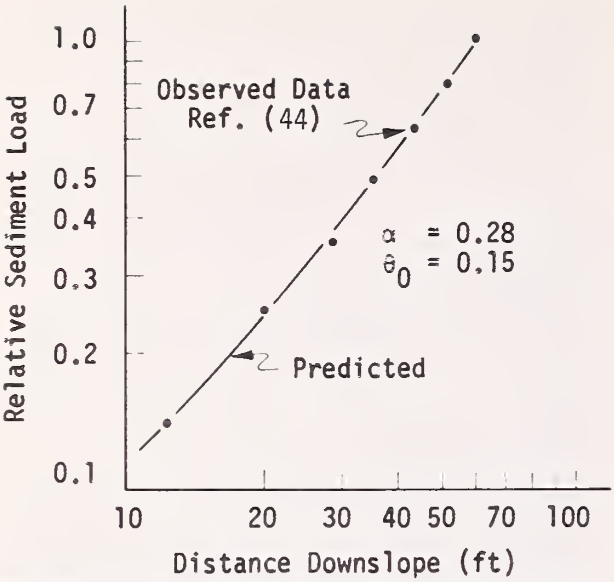

FIGURE 6.—Predicted distribution of sediment load along a uniform slope with severe interrill and rill erosion.

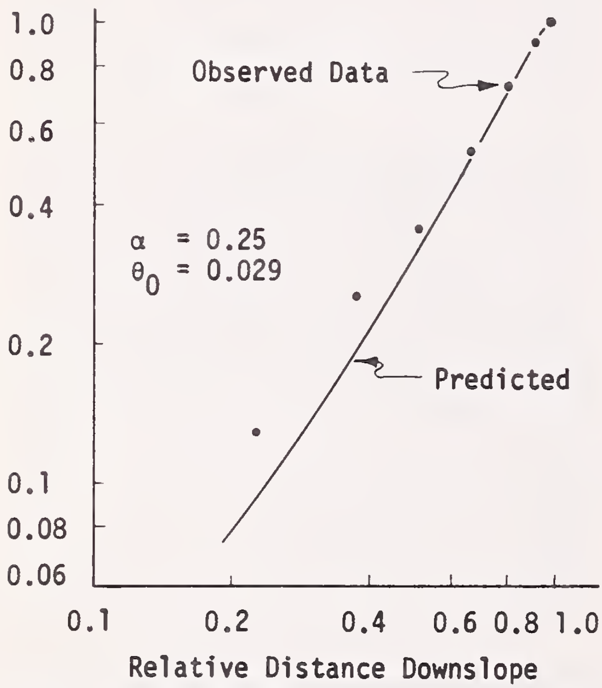

FIGURE 7.—Predicted distribution of sediment load along a uniform slope with severe rill erosion.

Deposition at the end of a uniform slope as given by Foster and Meyer (*8*) is

$$G_* = (G_{*e}) \exp [-\alpha_d (x_* - 1)], \qquad (13)$$

where α_d=deposition value of α
and $G_{*e} = G_*$ at $x_*=1$.

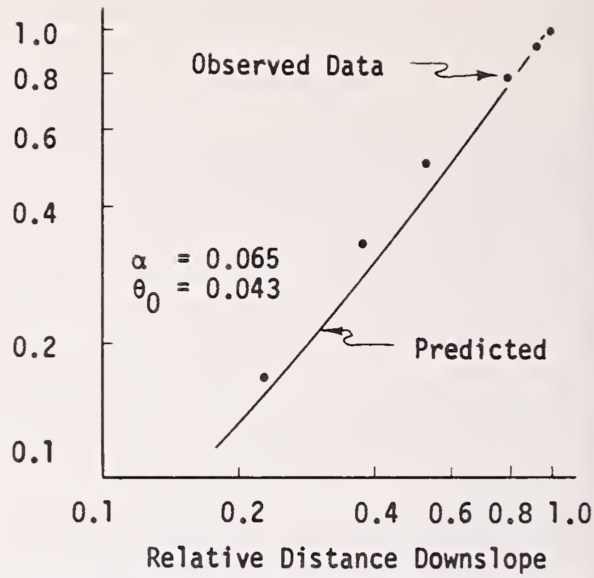

FIGURE 8.—Predicted distribution of sediment load along a uniform slope without severe rill erosion.

Equation 13 is based on the assumption that for $x_*>1$, $T_c=0$ and $\Theta=0$; by it, the sediment load and the rate of deposition decay exponentially with distance from the slope end of $x_*=1$.

Closed-form equations were also developed for nonuniform land profiles given by

$$Z_* = (1 - x_*)^m \text{ (concave)} \qquad (14)$$

and

$$Z_* = (1 - x_*^m) \text{ (convex)}, \qquad (15)$$

where $Z_* = h/H$,
h=elevation of the land profile at any x,
and H=difference in elevation between $x=0$ and $x=L$.

The slopes along these profiles are

$$S_* = m(1 - x_*)^{m-1} \quad \text{(concave)} \qquad (16)$$

and

$$S_* = m x_*^{m-1} \text{ (convex)}. \qquad (17)$$

The expressions for dg_*/dx_* are

$$dg_*/dx_* = m(1 - x_*)^{m-1} - m(m-1) x_* (1 - x_*)^{m-2} \quad \text{(concave)} \qquad (18)$$

and

$$dg_* dx_* = m^2 x_*^{m-1} \text{ (convex)}. \qquad (19)$$

Closed-form solutions for these slopes exist for integral values of m. However, when m exceeds 3 or is not an integer, the algebraic manipulations become excessive and numerical integration of equations 7 and 8 is simpler.

Closed-form solutions were obtained with

$m=2$ for the concave and convex slopes. Interrill detachment D_i was assumed to be independent of slope steepness, which gave $\Theta=\Theta_0$. Equations for the location and rate of maximum rilling, the rate of rilling along the slope, the sediment load along the slope, the location where deposition begins and deposition rates near the toe of concave slopes are developed. Such equations are helpful in developing erosion control practices for a slope or predicting the sediment yield for the slope.

The rate of detachment in the rills above the location where deposition begins at $x_*=x_d$ is given by

$$D_*=(2-\Theta_0)[1-\exp(-\alpha x_*)]-4\{\alpha x_*-[1-\exp(-\alpha x_*)]\}/\alpha, \tag{20}$$

and the sediment load is given by

$$G_*=2x_*(1-x_*)-D_*/\alpha. \tag{21}$$

The location of maximum rilling, where $dD_*/dx_*=0$, is given by

$$x_m=[\ln(\alpha/2+1-\Theta_0\alpha/4)]/\alpha. \tag{22}$$

The point of deposition is obtained from equation 20 by setting $D_*=0$. The result is

$$x_d=[\ln(1-4x_d/A)]/\alpha, \tag{23}$$

where $A=2-\Theta_0+4/\alpha$.

A closed-form solution for x_d was not found, but x_d can be determined numerically by a Newton-Rapson technique.

Where deposition is occurring, the boundary condition for equations 7 and 8 is $D_*=0$ at $x_*=x_d$. Also, Θ is taken as zero since particles from interrill area are assumed to deposit immediately upon entering the flow. Consequently, they have no effect on the sediment load. For deposition:

$$D_*=2\{1-\exp[-\alpha_d(x_*-x_d)]\}-4\{\alpha_d\{x_*-x_d\exp[-\alpha_d(x_*-x_d)]\}-\{1-\exp[-\alpha_d(x_*-x_d)]\}\}/\alpha_d \tag{24}$$

$$G_*=2x_*(1-x_*)-D_*/\alpha_d. \tag{25}$$

Since G_* lags g_*, the nondimensional transport capacity, G_* will not be zero at $x_*=1$, and equation 13 can be used to determine the sediment load beyond $x_*=1$.

The solution for a convex slope where $m=2$ is

$$D_*+4\{\alpha x_*-[1-\exp(-\alpha x_*)]\}/\alpha-\Theta_0[1-\exp(-\alpha x_*)] \tag{26}$$

and

$$G_*=2x_*^2-D_*/\alpha. \tag{27}$$

A plot of equations 10, 13, 21, 25, and 27 is shown in figure 9.

Equations 9 and 10 and 20 through 27 were evaluated for $\alpha=0.1$ and $\Theta_0=0.035$. For the uniform slope at $x_*=1, G_*=0.0817$, and $D_*=0.0918$. For the convex slope at $x_*=1$, $G_*=0.0983$, and $D_*=0.190$. The maximum D_* on the concave slope was 0.0467 at $x_m=0.48$. The maximum sediment load on this slope was 0.0640 at $x_d=0.967$. The sediment load delivered from the concave slope at $x_*=1$ was 0.0403. If the sediment yield from the uniform slope is 1, the sediment yields from the convex and concave slopes at $x_*=1$ are respectively 1.12 and 0.494. For a comparison, Young and Mutchler (*48*) observed the relative sediment yields of 1.00, 1.08, and 0.411 for the respective slope shapes of uniform, convex, and concave. Their tests were made during the first crop stage following the planting of corn cultivated up and down slope. However, Young and Mutchler's concave slope flattened only to approximately 2 pct. Their slope shape was not a complete curve as described by equation 14 for $0<x_*<1$. An m value of 2 was assumed, and using their $S_0=8.5$ pct, the end of their slope was at $x_*=0.88$ according to equation 16. The predicted relative sediment yield at $x_*=0.88$ is 0.69. No deposition above $x_*=0.88$ is predicted as they observed. However, based on their results for the uniform and convex slopes, deposition may have been due largely to the restricting end sill of their plots.

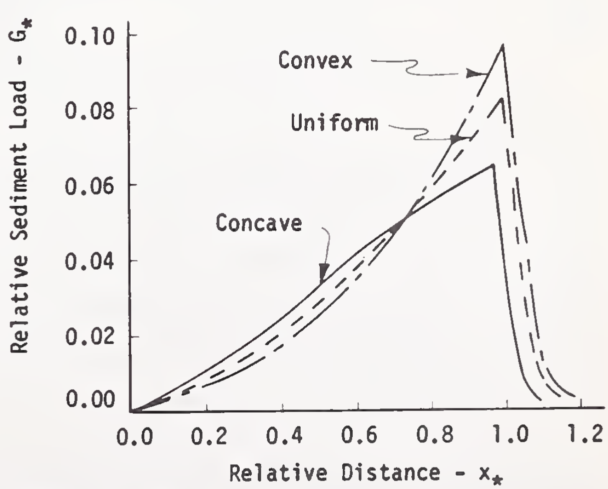

FIGURE 9.—Predicted relative sediment loads along three slope shapes.

The above deposition estimates for the concave slope were based on two important assumptions. First, deposition capacity was assumed numerically equal to the transport capacity, i.e., in the expression $D_c = C_d T_c$, $C_d = 1$. This was reasoned from the Yalin equation, since it is an erosion and deposition relationship for noncohesive particles based on the mechanics of saltation. Second, transport capacity was assumed to be the same for depositing conditions as for detaching conditions when flow rates and slopes are equal. However, the transport capacity decreases with deposition because the flow becomes broader and shallower. If this effect is brought into the analysis, the predicted sediment loads during deposition become less than indicated above.

The effect of the degree of concavity or convexity (different m values) can be studied by numerically integrating equations 7 and 8. The results are useful in a design application in selecting the best slope shape for a given design criterion.

Most topographic land profiles in nature are irregular. Equations 7 and 8 can be numerically integrated with g_* and Θ given as tables of values which are functions of x_*. Another possibility is to divide the irregular slope into a series of uniform slopes and apply equations 11 and 12 sequentially along the slope. The constant of integration C must be evaluated at each division point. Given the proper value of C, the erosion equations for each slope increment are

$$D_* = (S_* - \Theta)[1 + C \exp(-\alpha x_*)] \qquad (28)$$

and

$$G_* = x_* S_* - D_*/\alpha. \qquad (29)$$

The constant of integration for an increment is given by

$$C = [(D_{*u}/S_* - \Theta) - 1] \exp(\alpha x_{*u}) \qquad (30)$$

and

$$D_{*u} = \alpha(x_{*u} S_* - G_{*u}), \qquad (31)$$

where $x_{*u} = x_*$ of the upper end of the increment,
$G_{*u} = G_*$ at x_{*u},
and $D_{*u} = D_*$ at x_{*u}.

Continuity of the sediment load at x_{*u} is maintained, but the detachment rate at x_{*u} is discontinuous. Its value depends on whether the upslope or the downslope increment is used to make the evaluation. The results of applying equations 28 through 31 to the concave slope studied by Young and Mutchler (*47*) are shown in figure 10. The ratio of soil loss predicted from the concave slope to that predicted from a uniform slope is 0.84 compared to an observed 0.88 during the last 60 min of simulated rainfall. Figure 10 indicates a larger difference in the predicted soil loss ratio. The observed data in the figure is from microrelief measurements which can be subject to error.

If D_{*u} from equation 31 is negative, deposition is occurring on the increment and $\alpha = \alpha_d$ is used in equations 30 and 31. If the slope increment is sufficiently long, deposition will cease and erosion will occur on the lower portion of the increment. The equations for the deposition section of the increment are

$$D_{*u} = \alpha_d(x_{*u} S_* - G_{*u}), \qquad (32)$$

$$C = (D_{*u}/S_* - 1) \exp(\alpha_d x_{*u}), \qquad (33)$$

$$D_* = S_*[1 + C \exp(-\alpha_d x_*)], \qquad (34)$$

and

$$G_* = x_* S_* - D_*/\alpha_d, \qquad (35)$$

where no consideration is given to the effect of deposition on T_c. The location on the increment where deposition ends (i.e., $D_* = 0$) is given by

$$x_{de} = [-\ln(-1/C)]/\alpha_d. \qquad (36)$$

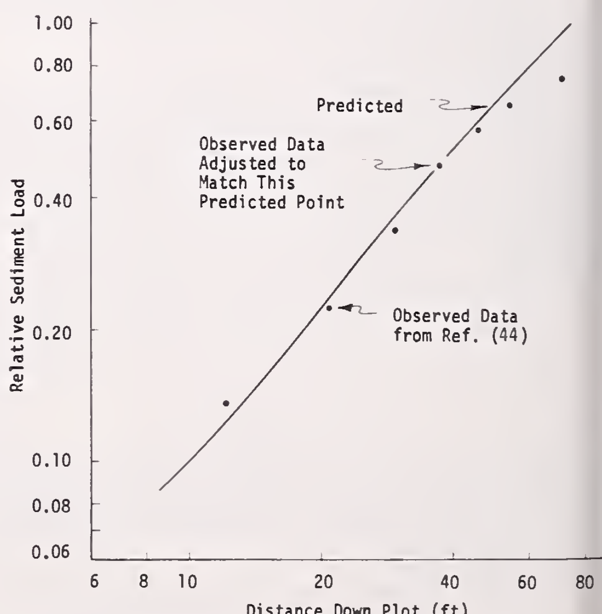

FIGURE 10.—Sediment load along a concave slope as predicted by dividing the slope into uniform increments.

At x_{de}, $G_* = x_{de}S_*$. For $x_* > x_{de}$, a new C is evaluated by equation 30 with $D_{*u}=0$ and $x_* = x_{de}$. The results of this technique applied to an irregular slope are shown in figure 11.

Erosion Equations Not Based on Equation 2

Although equations 7 and 8 are basic and fundamental erosion equations, they mask certain important effects of the erosion process. Neglect of the influence of sediment load on detachment rate as expressed in equation 2 is inconsequential for many relatively uniform slopes because the sediment load apparently fills only a small percent of T_c as indicated by table 2.

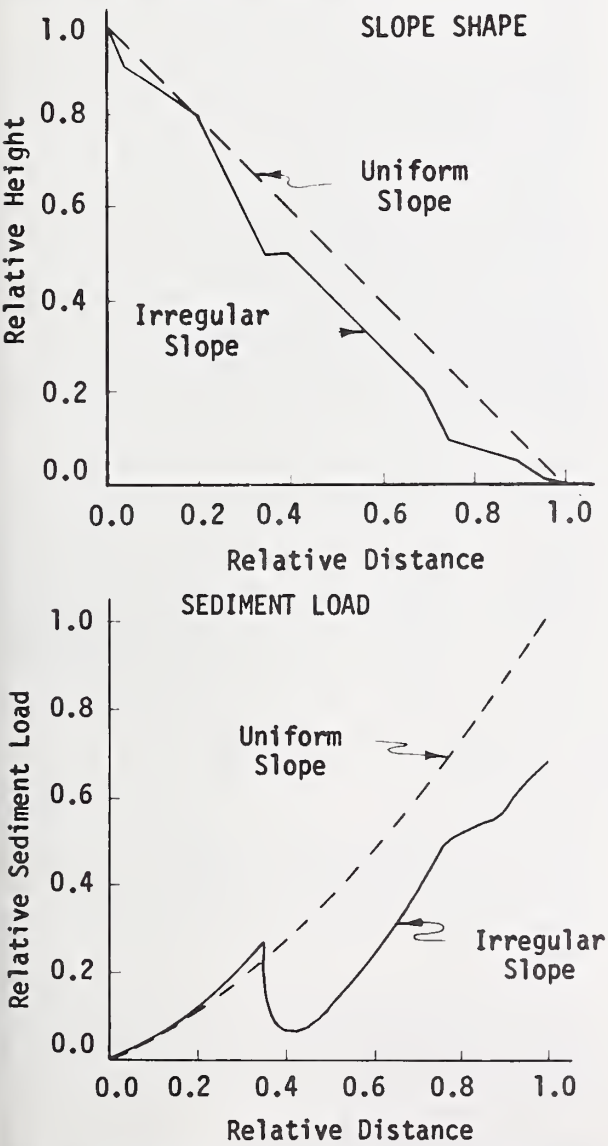

FIGURE 11.—Sediment load along an irregular slope as predicted by dividing the slope into uniform increments.

Where equation 2 is not used, the expressions for the delivery rates of particles from the interril areas to rill flow and for flow detachment capacity are used directly in the continuity equation, equation 1, to determine the sediment load, G. Making the same assumptions for the mechanics of subprocesses as were made in the preceding section, the expression for the sediment load due to interrill erosion is

$$G_i = D_i x, \tag{37}$$

the sediment load due to rill erosion is

$$G_r = C_{sr}\sigma S x^2/2, \tag{38}$$

and the total sediment load is

$$G = C_{sr}\sigma S x^2/2 + D_i x, \tag{39}$$

where C_{sr}=soil erodibility factor for rill erosion.

The relative contributions of G_r and G_i are dependent on several factors, including rainfall intensity, runoff rate, slope length, slope steepness, soil type, and surface microrelief. In the Palouse areas in the Northwest, G_i is believed to contribute little to the total sediment load, while in the Midwest, G_r apparently contributes little to G in some cases.

The effect of slope length on total soil loss from a uniform slope has often been expressed as $G \propto L^n$ (*43, 49*). Values of n were determined by plotting G versus L on a log-log scale and determining the slope of the resulting curve. Such an n is given by dY/dX, where $Y=\ln G$ and $X=\ln L$. Differentiation of equation 39 in this manner yields

$$n = 1 + \beta/(1+\beta), \tag{40}$$

where $\beta = G_r/G_i$.

Thus, n ranges from 1 for $\beta=0$ to 2 for an infinitely large β. In other words, n tends toward 1 if the contribution of interrill erosion relative to rill erosion is large, but n approaches 2 if interrill erosion is negligible. Therefore, factors that affect β will affect n. Those factors, as shown by equation 39, include slope steepness, slope length, infiltration rate, rainfall intensity, and the susceptibility of soil to rill erosion relative to its susceptibility to interrill erosion.

As slope length increases, n increases because of the x^2 term in G_r compared to x in G_i in equation 39. No slope length effect is contained in σ,

the excess rainfall rate, since Wischmeier (*39*) found that the runoff volume per unit area is usually independent of slope length. Also, for up-and-down slope cultivation, little interconnecting of rills is expected, and therefore an assumption of C_{sr} being independent of x is reasonable. Consequently, the slope-length effect is explained entirely by the x^2 and x terms.

As slope steepness increases, n increases provided interrill erosion increases less rapidly with S than does rill erosion. For conditions where raindrop detachment limits G_i, a decrease in infiltration rate increases runoff rate and thus also G_r, which gives a larger n. Also, under similar conditions, an increase in rainfall intensity decreases n because of the i^2 term in D_i and only a linear term of i in σ in the G_r expression. If erodibility of a soil with respect to flow is large, n will be larger, as experimental results show (*19*). For example, on a construction slope where mulches were studied (*20*), $G_r \simeq 3G_i$ and n was approximately 1.7. Also, a log-log plot of soil loss for this study versus simulated slope length showed the effect of surface cover. When the erosion protection of the surface cover failed and allowed rill erosion to accelerate, the value of n increased. Thus, experimental data verified at least the trend of equation 40. Also, equation 40 is consistent with the 1.3 to 1.6 range for n recommended by Wischmeier and Smith (*43*) for the universal soil loss equation.

The effect of slope steepness on soil loss has usually been expressed as $G \propto S^p$ (*46*) or as the quadratic function used in the universal soil loss equation. The exponent p is determined from a log-log plot of G versus S, or obtained from $dY/d\bar{S}=d(\ln G)/d(\ln S)$. The range of p is from 0 to 2 for the quadratic expression. It varies from 1.1 at a 4-pct slope to 1.7 at a 20-pct slope. Zingg (*46*) recommended a constant $p=1.4$. The value of p of equation 39 ranges from 0 to 1. The reasons for a difference between p in equation 39 and the universal soil loss equation are not fully known. However, the equations, although similar in form, are of different types. Equation 39 is a rate equation (i.e., weight/width/unit time). In order to make equation 39 equivalent to the universal soil loss equation (weight/width/storm period), it is necessary to integrate with respect to time for the duration of runoff for the given storm period. Since Wischmeier (*39*) showed that total runoff per unit area for a storm on agricultural land is a function of slope steepness, duration of runoff and runoff rates as well should be functions of S. Therefore, additional S-dependent terms are needed to account for the effect of slope steepness on runoff where equation 39 is developed to express total soil loss for a storm period. Also, rill density could be a function of S. If introduction of these S terms into the erosion expressions causes total rill erosion for a storm to become proportional to S^2 and total interrill erosion for a storm as proportional to $AS+B$, equation 39, developed to express total soil loss for a storm, takes on the same form as the universal soil loss equation with respect to slope steepness. However, under conditions where runoff rate, runoff duration, and rill density are independent of slope steepness, the indicated p of 0 to 1 should be reasonable. Steeper construction slopes, such as highway embankments, are examples of this condition.

EFFECT OF VEGETATION, PLANT RESIDUES, AND OTHER MULCHES

For erosion simulation to have maximum potential as a general erosion model, it must be capable of describing the effects of vegetation, plant residues, and other mulches. The effects of these materials can be divided into three zones: above the soil surface, at the soil surface, and within the soil (*40*). The effect within the soil is usually to modify the strength of the soil and the infiltration capacity of the soil. Provided this effect can be evaluated, it can be easily included in the simulation.

Above the surface, vegetation provides a canopy that reduces the energy of raindrop impact. The rate of soil detachment by raindrop impact is decreased and evidence indicates that reduction of raindrop impact energy may also decrease the capacity of flow to detach and transport (*16, 19*).

Material on the soil surface reduces the surface area exposed to direct raindrop impact and reduces flow velocity, thus increasing flow depth for equal discharges. On interrill areas, data (*19*) for straw mulch rates of less than 1 ton/acre indicated that the ratio of interrill soil loss with a given mulch rate to the soil loss from an unmulched surface is independent of slope steep-

ness for slopes less than 20 pct. This ratio was 0.62 for a 0.22-ton/acre mulch rate while it was 0.23 for a 0.89-ton/acre mulch rate. The independence of this ratio of slope steepness indicates that raindrop-impact detachment may be the controlling factor for these data. Thus mulch reduces interrill erosion in two ways.

First, mulch protects a portion of the interrill area from direct raindrop impact. This effect is approximated by $D_{im}=\xi D_i$, where D_{im} is the delivery rate of detached particles from the interrill areas when there is mulch and ξ is the decimal fraction of the soil surface left exposed by mulch. Figure 12 shows the variation of ξ with mulch rate for typical wheat straw.

Second, the extra depth of water on the surface due to decreased flow velocity when mulch is present cushions raindrop impact, resulting in decreased raindrop-impact detachment (*25*). Figure 12 estimates the soil loss ratios for the above data to be 0.75 compared to the observed 0.62, and 0.32 compared to the observed 0.23. The difference is attributed to the effect of increased depth on the reduction of raindrop-impact detachment. However, an added factor related to flow depth is the effect of mulch rate on infiltration. Higher mulch rates protect the soil surface from sealing, which results in higher infiltration rates on mulched surfaces than on bare soil (*18*). Higher infiltration rates produce lower runoff rates, which require shallower flow depths. Consequently, when the effect of mulch on flow depth and raindrop-impact cushioning is evaluated, both runoff rate and the effect of the mulch on flow velocity must be considered.

The other effect of material on the soil surface is to reduce rill erosion by reducing the shear stress exerted by the flow on the soil surface. The shear stress of the flow is distributed between the mulch pieces and the soil surface in much the same way that it is distributed between the grains and the bed forms in sediment-transport analyses. Only that part acting on the soil surface tends to detach soil particles. By this division of the shear stress, the authors (*9*) showed that

$$\tau_{ms}/\tau_{ss}=k^{2/3}, \tag{41}$$

where τ_{ms}=shear stress of the flow acting on the soil with mulch,
τ_{ss}=shear stress without mulch,
and k=cube of the ratio of the average flow velocity with mulch to the velocity without mulch under the same conditions of soil, slope, and runoff rate.

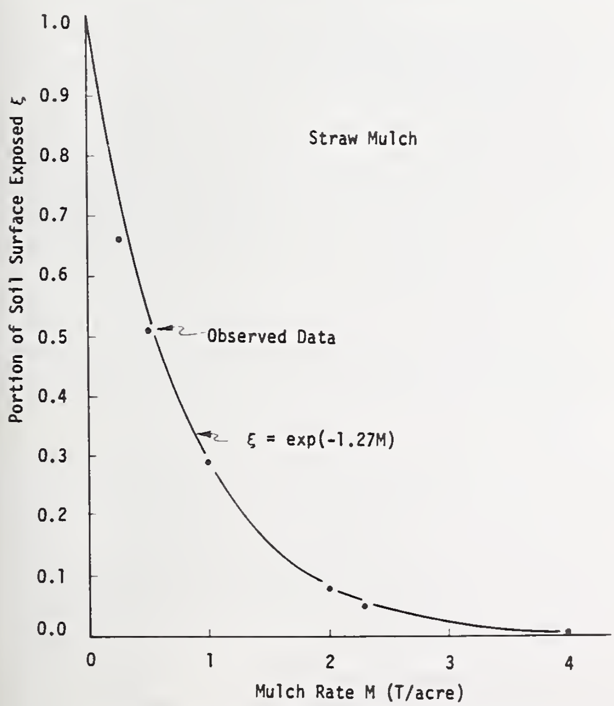

FIGURE 12.—Relationship between portion of soil surface exposed and mulch rate for wheat straw. (From Foster and Meyer *9*.)

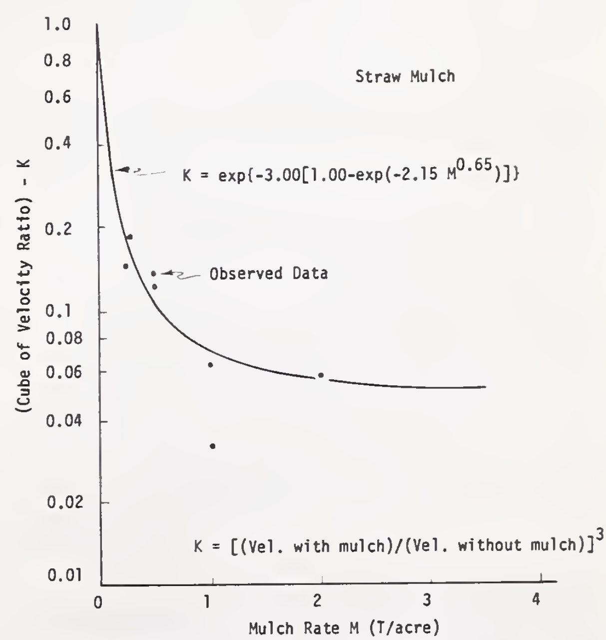

FIGURE 13.—Effect of straw mulch rate on runoff velocity. (From Foster and Meyer, *9*.)

Since D_c is proportional to $\tau^{3/2}$ from an earlier result, D_c and T_c are proportional to k. A plot of k versus mulch rate for wheat straw is shown in figure 13.

Figures 12 and 13 were used to evaluate the effect of straw mulch on interrill and rill erosion for three different soil and slope conditions. The results of estimating total erosion rates using this technique are shown in table 3. Similar encouraging results have been obtained for crushed stone and woodchip mulches (*9*).

TABLE 3.—*Comparison of predicted soil loss with observed soil loss from 35-ft erosion plots covered with wheat straw mulch*[1]

Mulch rate (tons/acre)	Fox loam, 15% slope		Xenia silt loam, 3% slope		Wea silt loam, 5% slope	
	Observed	Predicted[2]	Observed	Predicted[2]	Observed	Predicted[2]
¼	0.32	0.47	0.40	0.39	0.25	0.45
½	.31	.34	.25	.27	.16	.27
1	.19	.19	.12	.14	.029	.088
2	.040	.064	....	....	.....	.....
4	.024	.024	....	....	.....	.....

[1] From Foster and Meyer (*9*).
[2] Predictions are relative to soil loss from the no-mulch treatment.

CONCLUSIONS

Mathematical simulation of upland erosion by fundamental erosion mechanics has the potential for describing the erosion process at any point in time and at any location in the watershed. The sediment loads at all points and the erosion losses from any location can be determined. Furthermore, prediction of deposition from overland flow is an integral part of the simulation. Therefore, by using this type of analysis, a delivery ratio is not necessary for estimating the sediment yield of upland areas.

Two equations form the basis of the model: the continuity equation for mass transport and a sediment load-flow detachment interrelationship. In developing and solving these equations, the erosion process was separated according to the source area of sediment: interrill and rill erosion. Interrill erosion is a function of raindrop-impact detachment of soil particles and the transport capacity of the combined effects of raindrop impact and the thin sheet flow occurring on interrill areas. Rill erosion requires an analysis of the detachment capacity of rill flow, the transport capacity of rill flow, and the deposition potential of the sediment load from rill flow. Many of the relationships developed for streamflow seem applicable to rill flow.

This type of erosion simulation requires a hydrologic model of the watershed runoff. A kinematic overland flow model provides the inputs for the erosion simulation technique as developed herein. Erosion simulations using such a runoff model were made for 35-ft erosion plots. The predicted results compared favorably with observed results.

The erosion model was reduced to equation form. The resulting equations provided a simpler means of analyzing the erosion characteristics of less complex areas, such as developmental sites. Furthermore, these equations revealed characteristics of the erosion process that are useful in interpreting some earlier research findings. An example is a logical explanation of the variation found in the length exponent as used in empirical erosion equations.

The effects of vegetation and mulches on the mechanics of erosion were considered. Those effects can be included in the erosion simulation to make it a more general model.

The erosion simulation model as described herein is not ready for universal application to design problems. Many of the basic relationships have not been fully developed. Also, information is not available concerning the erodibility of various soils with respect to erosion by either raindrop impact or flow, and little is known about rill formation. However, to a limited degree, these techniques can be applied to problems such as the design of slope shapes, selection of mulch rates, and estimates of sediment yields

for less complex areas (such as construction sites), if the user understands the assumptions used in the development of the equations. These techniques are also being used to better understand and interpret previous research findings. One of the greatest benefits to date is that the development of these analyses clearly shows areas of deficient knowledge and can consequently guide in the planning of future research that will be productive and beneficial.

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APPENDIX.—MATHEMATICAL NOTATION

- a Exponent in equation for D_c.
- A Term given by $2-\Theta_0+4/\alpha$.
- A_i Total amount of detachment on an interrill area during a rainstorm (weight/area).
- C Constant of integration.
- C_d Coefficient relating rate of deposition to the difference between transport capacity and sediment load.
- C_D Coefficient relating tractive force (shear stress) to detachment capacity.
- C_i Constant relating kinetic energy per unit of rainfall to rainfall intensity.

C_{si} Coefficient for transportability of detached particles in interrill flow.

C_{so} Constant to account for the transport capacity of interrill flow at zero slope.

C_{sr} Coefficient relating soil factors to rill erosion.

C_T Coefficient relating tractive force (shear stress) to transport capacity.

C_τ Coefficient in equation for D_c.

d_r Dispersion ratio.

D_* Relative rill detachment rate, $D_*=LD_r/T_{co}$.

D_{*u} Relative rill detachment at the upper end of a slope increment.

D_c Detachment capacity of rill flow at a location (weight/unit area/time).

D_{co} Detachment capacity of rill flow at the end of a uniform slope (weight/unit area/time).

D_d Deposition rate (negative detachment rate) from sediment load in rill flow (weight/unit area/time).

D_i Delivery rate of detached soil particles from interrill areas to rill flow (weight/unit area/time).

D_{im} Delivery rate of detached soil particles from interrill areas when mulch is present.

D_{io} Interrill delivery rate on reference uniform slope (weight/area/time).

D_{i*} Interrill delivery rate relative to interrill delivery rate from reference uniform slope.

D_r Flow detachment rate in the rills at a location (weight/unit area/time).

D_{tci} Transport capacity per unit area of interrill flow (weight/unit area/time).

e Kinetic energy per unit of rainfall (force-distance/unit area/unit of rainfall).

E_{ke} Total kinetic energy of a rainstorm (force-distance/unit area).

f Darcy-Weisbach coefficient of friction for runoff model.

g_* Relative detachment or transport capacity, $g_*=D_c/D_{co}$ or T_c/T_{co}.

g Acceleration of gravity (32.2 ft/s^2).

G Sediment load of flow at any location on a slope (weight/unit width/time).

G_* Relative sediment load, $G_*=G/T_{co}$.

G_{*e} Relative sediment load at $x_*=1$.

G_{*u} Relative sediment load at the upper end of a slope increment.

G_i Sediment load due to interrill erosion (weight/width/time).

G_r Sediment load due to rill erosion (weight/width/time).

h Elevation along land profile.

H Difference in elevation of land profile between $x=0$ and $x=L$.

i Rainfall intensity (depth/time).

i_{30} Maximum 30-min intensity (inches/hour).

k Cube of the ratio of the flow velocity with mulch to the velocity without mulch.

K_{BJ}, K_F Coefficient for effect of soil properties on interrill detachment.

L Length of land profile.

L_i Length of interrill slope.

m Exponent in land profile equation.

n Slope of log-log plot of sediment load versus distance.

p Slope of the log-log curve of sediment load versus slope steepness.

q Discharge on the land profile (volume/unit width/time).

q_{oi} Discharge on interrill areas (volume/unit width/time).

S Slope steepness of land profile.

$\overline{S}$ Logarithm transformation, $\overline{S}=\ln S$.

S_* Relative slope along a land profile, $S_*=S/S_0$.

S_i Slope of interrill area.

S_0 Slope of the reference uniform profile that passes through the end points of the given land profile.

t Time.

T_c Flow-transport capacity at a location (weight/unit width/time).

T_{co} Rill-flow transport capacity at the end of a uniform slope (weight/unit width/time).

T_{ci} Transport capacity of interrill flow (weight/unit width/time).

x Distance from the upper slope end.

x_* Relative distance, $x_*=x/L$.

x_{*u} Relative distance of the upper end of a slope increment.

x_{de} Relative distance where deposition ends.

x_d Relative distance where deposition begins.

x_m Relative distance of point of maximum rill detachment rate.

X Logarithm transformation, $X=\ln x_*$.

$\overline{y}$ Average flow depth from runoff model.

Y Logarithm transformation, $Y=\ln G_*$.

Z_* Relative elevation of land profile, $Z_*=h/H$.

α Rill erosion parameter, $\alpha=LD_{co}/T_{co}$.

α_d Deposition parameter, $\alpha_d=LC_d$.

β Ratio of interrill sediment load to rill sediment load, $\beta=G_r/G_i$.

γ Weight density of runoff (weight/volume).

Δx_* Increment length of relative distance.

Θ Interrill erosion parameter, $\Theta=LD_i/T_{co}$.

Θ_0 Interrill erosion parameter for reference uniform slope.

ξ Decimal fraction of soil surface area left exposed by a given mulch rate.

σ Excess rainfall rate = rainfall intensity − infiltration rate (depth/time).

τ Average tractive force (shear stress) at a location (force/area).

τ_{cr} Critical tractive force of the soil (force/area).

τ_{ms} Average shear stress exerted by flow on the soil surface when mulch is present.

τ_{ss} Average shear stress exerted by flow on a soil surface with no mulch present.

Φ Constant describing rate of increase of interrill transport capacity with rainfall intensity.

USING A SCOUR AND DEPOSITION MODEL TO DETERMINE SEDIMENT YIELD

By William A. Thomas[1]

INTRODUCTION

The computer program described in this paper was designed for use in analyzing the effect of a reservoir or channel modification on the capability of a stream to transport sediment. The sediment yield of a stream is important input information to such a study, but average annual values are not sufficient when both scour and depositon occur. In such cases it is necessary to relate sediment load to water discharge and study the response of the stream to the water-sediment mixture during a hydrograph of flows. The water-sediment relationship is calibrated to produce the proper sediment yield, when integrated with respect to time, while insuring that the simulation will maintain the proper bed profile throughout the study area.

If the inflowing sediment load is too large, the model will respond by increasing its bottom slope and water velocity until a new flow condition that will transport the inflowing sediment load is established. On the other hand, if the inflowing load is too small, the flow will attack the model bed to establish the proper sediment transport for the hydraulic conditions and thereby decrease bed slope and water velocity. This continuity of sediment material is a valuable consideration when determining the total bed-material load and the locations where bed material is contributed by lateral inflow from sources other than the channel. A brief discussion about the capability of the model will be followed by an example problem.

CAPABILITY OF COMPUTER PROGRAM

The movable-boundary problem is simplified into one involving only a movable bed in the channel. The horizontal location of the channel banks is considered fixed, and the flood plain on each side of the channel is considered as having a fixed ground surface. This is similar in concept to the movable-bed hydraulic model.

By entering a sequence of water discharges from a discharge hydrograph, changes are calculated with respect to time and with respect to distance along the model for the following: total bed material, volume and gradation of material deposited, armoring of the bed surface, sediment load and gradation of material passing each cross section, and resulting bed elevation. In addition, sediment outflow at the downstream end of the model is calculated. The location and amount of material that has to be dredged is calculated if that option is desired.

The geometry of the physical system is represented by cross sections specified by coordinate points (stations and elevations) and the distance between them. Hydraulic roughness is measured by Manning's n-values, and it can vary in space from cross section to cross section, in elevation at each cross section, and along each cross section as required to reflect prototype conditions.

The water discharge hydrograph is approximated by a sequence of steady flow discharges, each of which flows for a specified number of days. Water surface profiles are calculated by using the standard step method to solve the energy equation. Friction loss is calculated by Manning's equation, and expansion and contraction losses will be included if the respective loss coefficients are specified. The velocity distribution across each section is calculated unless this option is suppressed.

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It is necessary to specify the water-surface elevation at the downstream end of the model so that water-surface profile calculations can begin. In the case of a reservoir the operating policy is utilized, but if open river conditions exist, a stage discharge rating curve is usually specified for the downstream end of the model.

The inflowing sediment load is related to water discharge by a rating table at the upstream end of the model. If the gradation of material in the bed is known—and it must be if realistic depths of scour of the bed are required—this gradation is specified for each cross section. (However, if only deposition is expected, the gradation of material in the bed can be calculated by the program, based upon the inflowing water-sediment mixture.)

Sediment mixtures are classified by grain-size fraction according to the American Geophysical Union scale. The program transports five fractions of gravel, from very fine (2 mm) to very coarse (64 mm), and five fractions of sand from very fine (0.0625 mm) to very coarse (2 mm).

Transport capacity is calculated at each cross section by using hydraulic data obtained during the calculation of water-surface profiles (e.g., width, depth, slope, and velocity of flow) and the gradation of bed material for that cross section.

Three options are available for calculating transport capacity: Toffaleti's application of Einstein's bedload function,[2] Laursen's relationship as modified by Madden for large rivers,[3] or a special relationship developed for the particular study and specified as transport capacity per unit of width versus the water depth-energy slope product.

INPUT DATA REQUIREMENTS

In simulation studies it is important for the engineer to apply the computer to his study rather than spending his time simplifying and approximating the study until it will fit the requirements dictated by a computer program. Detailed sediment studies involve large amounts of data, whereas the more general case involves studies in which only a small amount of data is available. These are conflicting requirements so far as computer programing is concerned, and such conflict often diminishes the usefulness of a program. In this program, provision has been made to accept as little or as much data as available and to analyze it. Therefore, the program is useful over a wide range of studies. Of course, the results are no more dependable than the data used to obtain them.

EXAMPLE APPLICATION

To illustrate the use of the program, a sample study is presented in which the bed-material load for the Trinity River near Romayor, Tex. (river mile 94.3) is being established. Basic data are grouped into four major categories:

1. Geometry of the stream as defined by cross sections and reach lengths (geometric model).
2. A description, by grain-size classification, of the inflowing water versus sediment discharge and the sediment material in the bed of the stream (the sediment model).
3. Streamflow hydrographs (the hydrologic model).
4. A description of the water-surface elevations at the downstream end of the model (the operating rule).

The Geometric Model

Figure 1 shows a typical cross section of the river channel and flood plain in the study reach. The limits of the movable bed are shown on the cross section. All bed-material load is considered to move within the movable-bed portion of the section. Nine sections were used to describe the study area.

The Sediment Model

The gradation curves shown in figure 2 were compiled from grab samples of surface material in the bed and banks. Each curve represents a different water discharge since each is at a dif-

[2] Toffaleti, F. B. 1968. A procedure for computation of the total river sand discharge and detailed distribution, bed to surface. U.S. Army Corps of Engineers Committee on Channel Stabilization Technical Report No. 5, 172 pp. Vicksburg, Miss.

[3] Madden, E. B. 1965. Channel design for modified sediment regime conditions on the Arkansas River. *In* Proceedings of the Federal Inter-Agency Sedimentation Conference 1963, pp. 335–352. U.S. Department of Agriculture Miscellaneous Publication No. 970.

ferent elevation, and the samples were made during a period when the water surface was lower than all sample points.

Figure 3 shows data points for the suspended-sediment load passing the Romayor gage. Figures 2 and 3 are actually redundant data sources and, therefore, one must complement the other when they are used together in the sediment model. That is, the size and gradation of material in the bed must produce the size and gradation of suspended material at the Romayor gage when the sediment transport equations are applied. Otherwise, one of these data sources is not valid.

The maximum grain size sampled in the bed is 0.59 mm. Therefore, the sand load in the streambed (curve 2, fig. 2) can be subdivided into, at most, four grain-size classifications, as follows:

Classification	*Grain diameter,* mm	*Fraction of total sample*
Very fine sand	0.0625–0.125	0.51
Fine sand	.125 – .250	.35
Medium sand	.250 – .500	.02
Coarse sand	.500 –1.000	.01

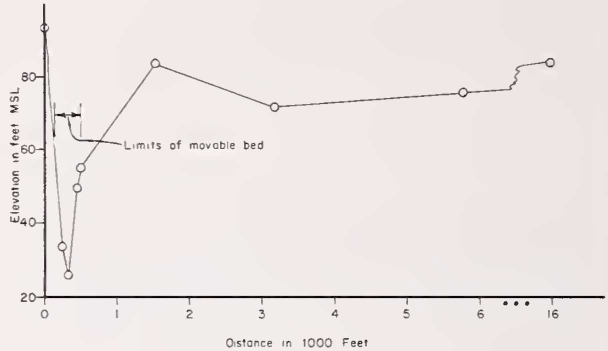

FIGURE 1.—Sample cross section.

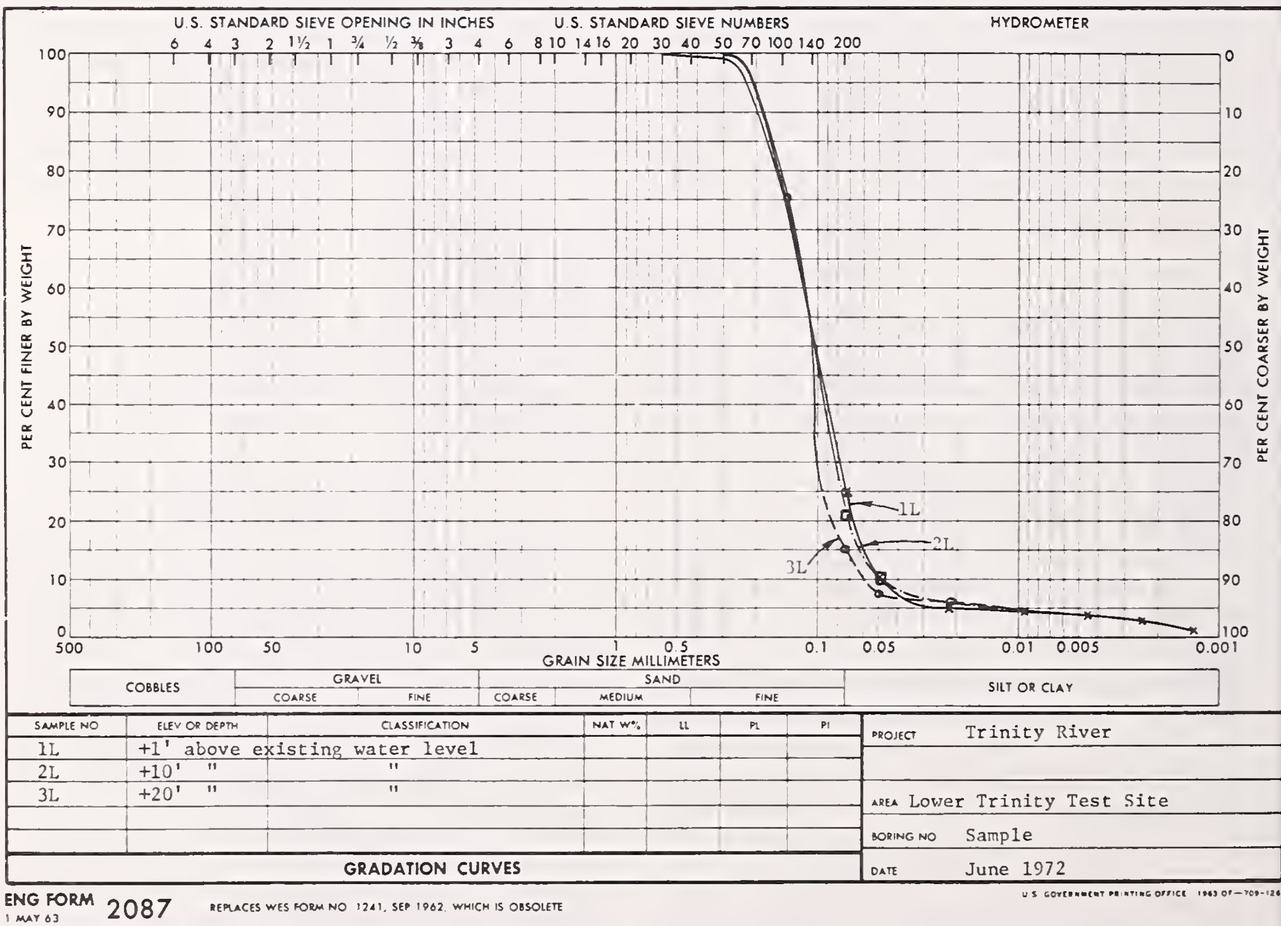

FIGURE 2.—Gradation of bed surface.

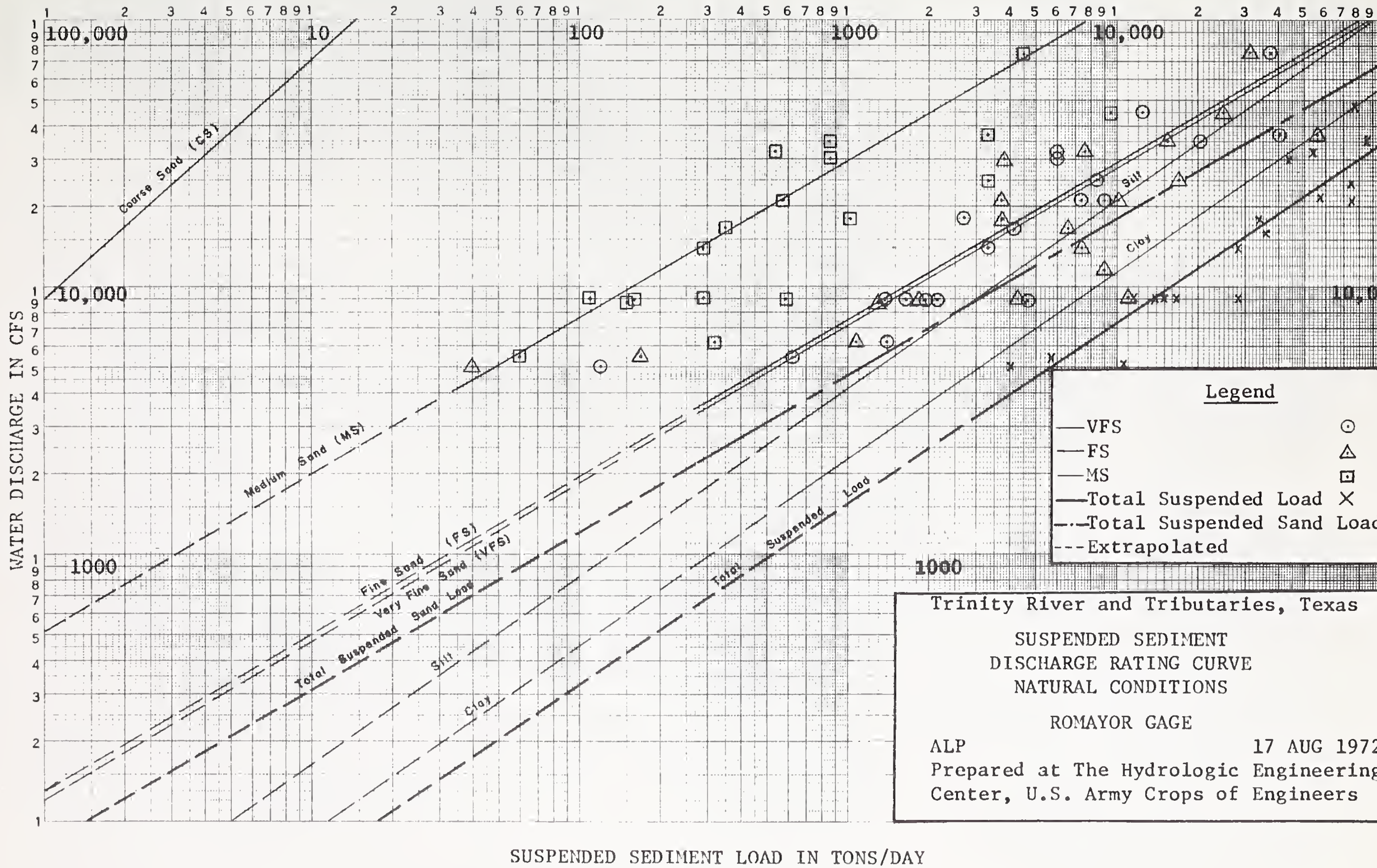

FIGURE 3.—Suspended-sediment load.

The Hydrologic Model

Figure 4 shows a sample year of the 5-yr discharge hydrograph after it was converted into a discharge histogram. The 5-yr histogram was passed through the study area one discharge at a time, and after each discharge, all cross sections were adjusted for scour and deposition. There are no major tributaries; therefore, all flow enters at the upstream end and passes out at the downstream end of the study area.

Curve 2 gradation was used because the corresponding water discharge was the same as the first discharge in the hydrograph to be analyzed.

The Operating Rule

The term "operating rule" is more applicable to cases where a dam forms the downstream boundary of the study area and reservoir levels fluctuate according to a rule curve. In this case no dam is present and water levels at the downstream boundary are directly related to water discharge by a discharge rating curve.

Response of Model

Figure 5 shows the bed profile at the beginning and at the end of the 5-yr hydrograph. There is essentially no change to this profile, even in the deep hole at mile 108.6. This indicates the proper

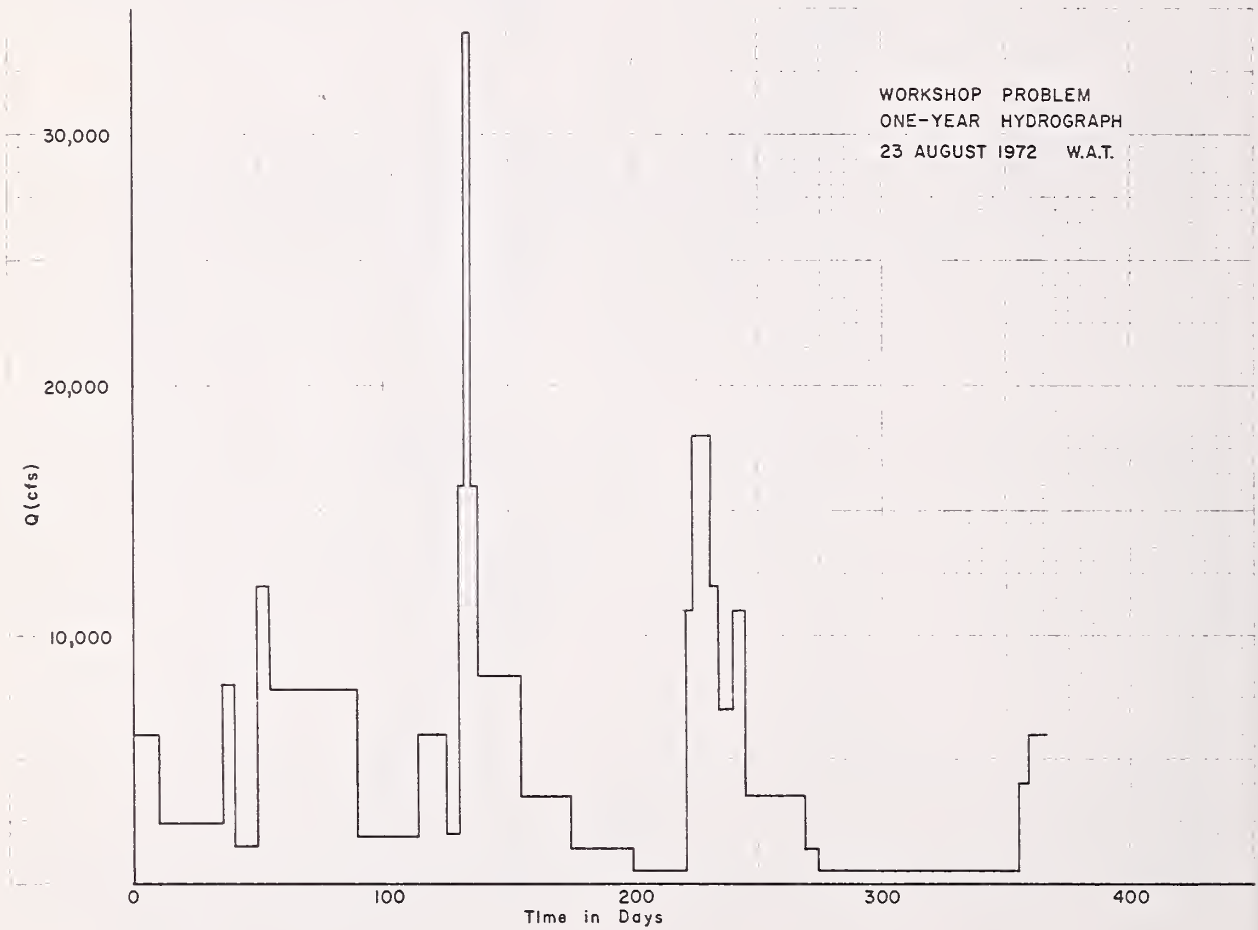

FIGURE 4.—Water discharge histogram.

inflowing sediment load has been determined for this model.

The following table shows accumulated inflowing and outflowing sediment loads. Again, no trend is established for the model to either scour or deposit.

Year	Accumulated volume in acre-feet			
	Inflow	Outflow	Difference	
1960	1,139	1,489	−350	
				−60
1961	1,413	1,823	−410	
				−26
1962	1,528	1,964	−436	
				−22
1963	1,632	2,090	−458	
				−18
1964	2,199	2,675	−476	

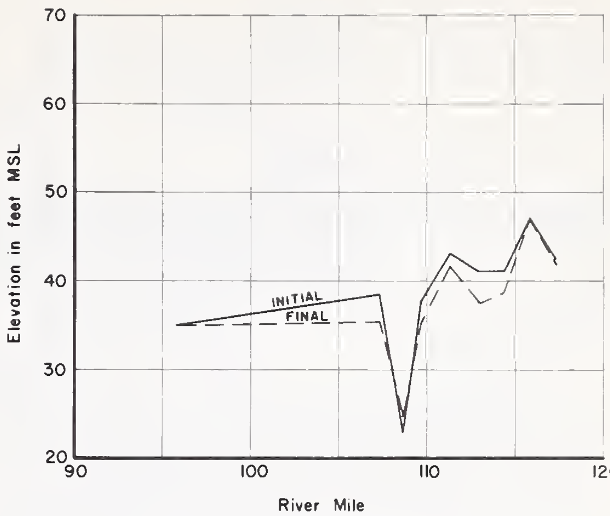

FIGURE 5.—Bed profiles.

CONCLUSION

Calculations based on the gradation curves for the streambed (fig. 2) produced suspended loads that agree closely with those presented in figure 3. As a result, the load curves of figure 3 will be satisfactory for use in this computer program for assessing the impact of a channel modification on the ability of the river to transport sediment through this reach. Moreover, if these curves were integrated with the flow duration curve, the expected annual sand yield for the Trinity River at Romayor would result.

POTENTIALS OF USDAHL MODELS FOR SEDIMENT-YIELD PREDICTIONS

By H. N. Holtan, C. L. Yen, and G. H. Comer[1]

INTRODUCTION

Comprehensive modeling of watershed hydrology can serve a great many purposes. We welcome this invitation to discuss the USDA Hydrograph Laboratory's (USDAHL) potential for contributing to the solution of soil-erosion and sediment-transport problems. Water transports sediment, and the hydrologic performance of agricultural watersheds is a full-time concern of USDAHL. The sequential paths of water across the watershed and through its drainage system bear directly upon the capacity of flows to detach and transport particles of soil. Two models under study in our laboratory are unique in their capacities for the time and space sequencing of waterflow. The "USDAHL-70 Model of Watershed Hydrology" is published,[2] and the "USDAHL 3-Tube Model of Flood Routing" is currently under development.

USDAHL-70 MODEL OF WATERSHED HYDROLOGY

With the use of USDAHL-70, computations and printouts can be obtained for overland flow, infiltration, evapotranspiration, subsurface return flow, deep seepage, and resulting soil moisture status for discrete zones of soil-land use complexes on a watershed. Input and computations use variable time increments, and results can be printed out in detail or as summaries, for example, of daily or monthly values. The model can be applied to a watershed having several zones, with or without cascades of flow from one zone to another, or it can be applied to a single zone of soil-cover complex. We have used hypothetical cases to demonstrate the type of output obtainable from the model. A soil having 12 inches of A-horizon is assumed in these calculations. Results may differ greatly for soils having thicker or thinner topsoils because the A-horizon greatly influences infiltration.

Monthly accumulations of subsurface return flow, overland flow, and the daily status of soil moisture computed for a hypothetical annual rainfall on a hypothetical soil are presented for corn in figure 1 and for grass in figure 2. The path of flow, i.e., surface or subsurface, is important in that only surface flows carry sediment. Vegetative density increases infiltration. Therefore, lesser infiltration and greater surface flow occur on corn than on grass. Corn also affords lesser protection to the soil against par-

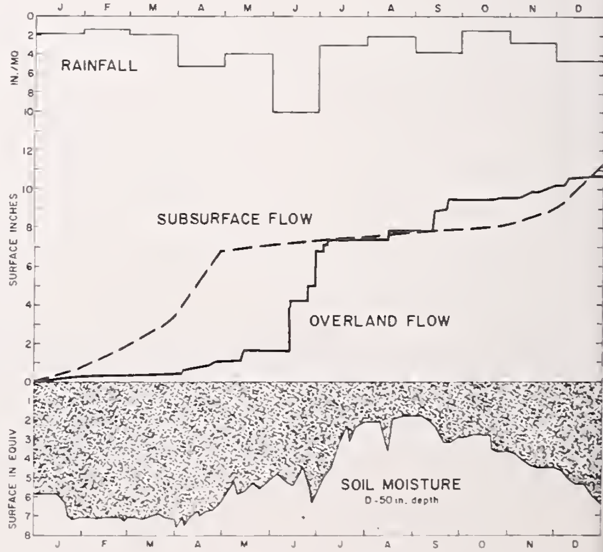

FIGURE 1.—Flow distribution for deep soil in cornland (hypothetical), computed by USDAHL-70 model.

[1] Hydraulic engineers, USDA Hydrograph Laboratory, Soil, Water and Air Sciences, Agricultural Research Service, Beltsville, Md. 20705.

[2] Holtan, H. N., and Lopez, N. C. 1971. USDAHL-70 model of watershed hydrology. U.S. Department of Agriculture Technical Bulletin No. 1435, 84 pp.

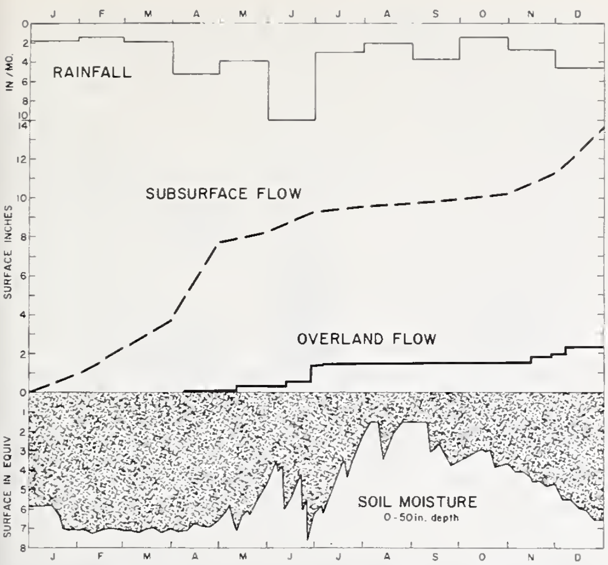

FIGURE 2.—Flow distribution for deep soil in bluegrassland (hypothetical), computed by USDAHL-70 model.

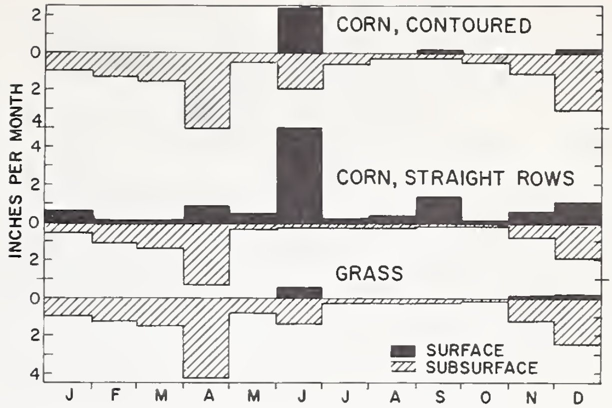

FIGURE 3.—Surface and subsurface flows for cornland and grassland (hypothetical), computed by USDAHL-70 model.

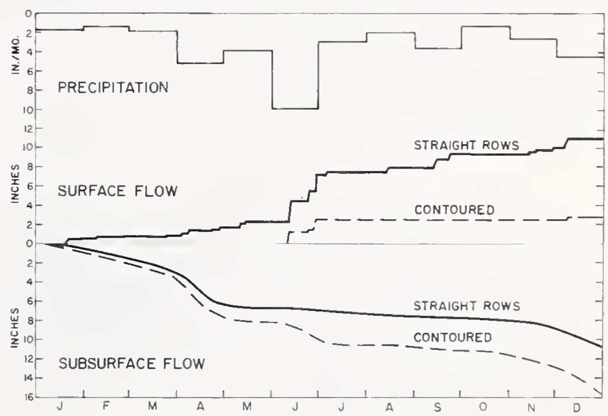

FIGURE 4.—Surface and subsurface flows for cornland (hypothetical), computed by USDAHL-70 model.

ticle detachment by rainfall impact. The accumulated flows and the moisture status given in figures 1 and 2 are also of interest in problems of water pollution by solubles.

Monthly volumes of surface and subsurface flows for contoured-row corn, straight-row corn, and grass are given in figure 3. In the case of corn, fertilizers are incorporated into the soil usually in May after subsurface flows have practically ceased. Subsurface flows in the late fall are exposed only to those fertilizers unused by summer crops. Surface additives such as pesticides and other agricultural chemicals may be removed by overland flows predominant during the growing season of corn. In grassland, most chemical additives are applied on the land surface, whereas most of the flow follows a subsurface route. Thus, land use determines the type and placement of chemical additives and also greatly influences the path of excess water. Both must be considered in questions of pollution from chemical additives in agriculture. Tillage practices also greatly influence the paths of flow. Corn planted in straight rows (fig. 4) yielded about 4 times as much accumulative surface runoff and about three-fourths as much accumulative subsurface flow as did corn planted on the contour. This is a significant difference in the erosion forces of surface runoff. The time of flow occurrence may also be important. In figure 4, it appears that, for this rainfall distribution on this soil, more subsurface flow is likely to occur later in June and July, after placement of fertilizers, if the corn is planted on the contour. Perhaps we need more research on this possibility. Differences in total outflow (surface plus subsurface) from straight rows (21.9 inches) and from contoured rows (18.8 inches) are due to greater moisture content for evapotranspiration under contoured rows.

Planting corn on the contour also reduced the velocity of overland flow. The hydrographs in figure 5, for corn in straight rows up and down hill and for corn on the contour, were obtained in the USDAHL-70 model by routing rainfall in excess of infiltration through applications of continuity and the equation of overland flow.

$$q = aD_a^{\,n}, \qquad (1)$$

where q=overland flow rate in surface inches per hour,

a=the rate of overland flow produced by an average depth of 1 inch,

n=a constant, 3.0 for laminar flow and 1.67 for turbulent flow,

and D_a=average depth of flow in inches.

The value of a varies directly as the slope for laminar flow and directly as the square root of slope for turbulent flow; however, a is inversely related to length of flow path when expressed in surface inches per hour. In figure 5, the value of a was assumed equal to 0.1 inch/h for contoured rows and equal to 100 inches/h for rows running up and down hill.

With assumed laminar flow, peak flows for straight rows of corn in figure 5 are approximately 5 times as great as the peaks computed for contoured corn. The erosion potentials are, perhaps, in a similar ratio.

The average depth over an area of flow can be computed as

$$D_a = (q/a)^{1/n}. \qquad (2)$$

Thus, the maximum value of D_a for straight rows was $(1.87/100)^{0.33}$, or 0.2654 inch, and for contoured rows the maximum D_a was equal to 1.57 inches average depth. The average depth of a given flow rate can be used to compute an index of peak average velocity:

$$\bar{v} = (q/D_a), \qquad (3)$$

where $\bar{v}$=average velocity in linear inches per hour per unit length.

Computed average velocity at peak flow was 1.87/0.2654=7.046 inches/h/inch of flow length for straight rows, compared to 0.248 inch/h for contoured rows of corn. If these peaks of overland flow were computed for slopes 1,000 ft in length, the average velocities would be 1.96 ft/s and 0.07 ft/s for straight rows and contoured rows, respectively. A velocity reduction in the ratio of 28 to 1.0 is undoubtedly significant in erosion potentials.

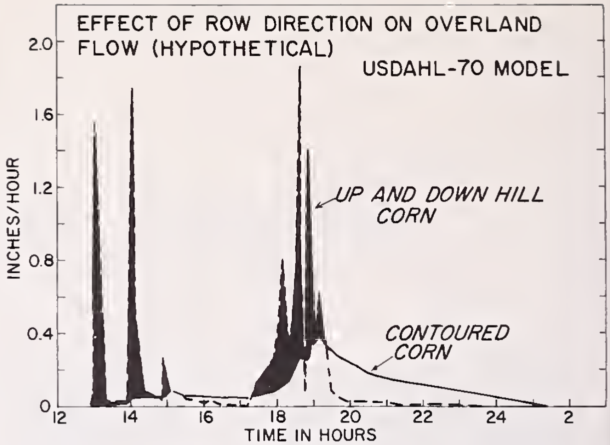

FIGURE 5.—Effect of row direction on overland flow (hypothetical).

The average depth of expected peak flow is also of interest in the design of terraces or row gradients. In corn rows, if the flow is concentrated on about one-third the area, D_a equal to 1.57 inches would be almost 5 inches deep between contoured rows on this soil. This may pose problems of overtopping and thus indicate a need for some minimum row gradient for a particular soil-cover combination.

The hypothetical case is used here to illustrate potentials of the USDAHL-70 model. These facets of computation are to be tested and improved through applications to the ARS research plots at Holley Springs, Miss., and to the tributary areas of Pigeon Roost Experimental Watershed under an existing cooperative study by the USDA Sedimentation Laboratory and USDAHL.

USDAHL 3-TUBE MODEL OF FLOOD ROUTING

The second model, USDAHL 3-tube model of flood routing, will also be tested and improved under the cooperative study by the two laboratories. Flood-routing techniques in current practice are based on the assumption that the water surface must be level across a given cross section; hence, velocities are represented as the average of channel and flood-plain flow. With the USDAHL 3-tube model, the method of characteristics[3] is used to solve discretely for water-surface elevations in the main channel, the left flood plain, and the right flood plain. The result is an uneven water surface due to differences in gradient, roughness, depth, and length of flow. Interactions tending toward a level surface are computed with wave velocity for lateral flow to or from the main channel. The two solutions, longitudinal and lateral, are iterated for each time increment until the increment of change in elevation is within some adopted limit.

[3] Henderson, F. M. 1966. Open channel flow. 522 pp. Macmillan, New York.

A convex water surface typical of a rising stream is illustrated in figure 6 for a hypothetical reach of six cross sections (stations) used in this study. Arrows imply that resultant flows from channel to flood plains are computed by the model. The critical-depth weir at the last station is assumed in order to eliminate backwater effects from downstream reaches. Figure 7 presents the hypothetical hydrograph of inflow to station 1. Many imperfect assumptions are still evident, but this is a discussion of potentials of model contribution, not necessarily of refined results. The medium for translation to sediment studies is envisioned to be velocities and changes in velocities.

Velocities in the channel and on each flood plain are given in figures 8 and 9 as computed for stations 1 and 3, respectively, based on equal coefficients of roughness, *n*. If average velocities were used in sediment-transport computations, they would obliterate the differences in transport capacities of the main channel and the flood plains. The greater difference between channel and flood-plain velocities at station 1 is due to an assumption that more inflow to the reach entered directly to the channel; inflow entered the reach in the proportions of existing flows in the three tubes at station 1. At station 3, the flood plains have received lateral flow from the channel, over the distance from station 1 to station 3, but even at station 3 the average velocity is a poor index of sediment-transport capacity. As depicted in figures 10 and 11, a roughness coefficient on the flood plains equal to twice that of the channel gives an even greater range in velocities.

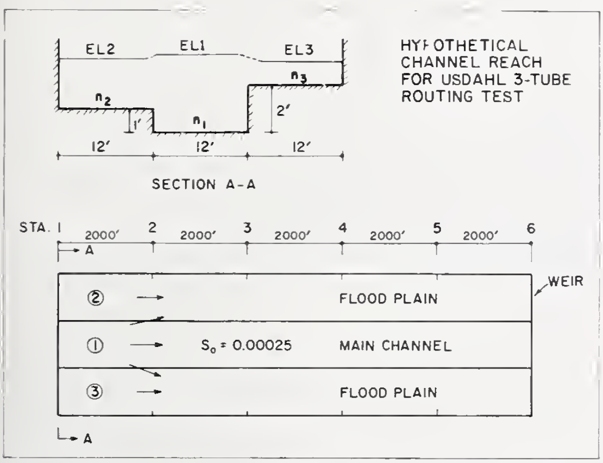

FIGURE 6.—Hypothetical channel reach of six stations used in the USDAHL 3-tube routing test.

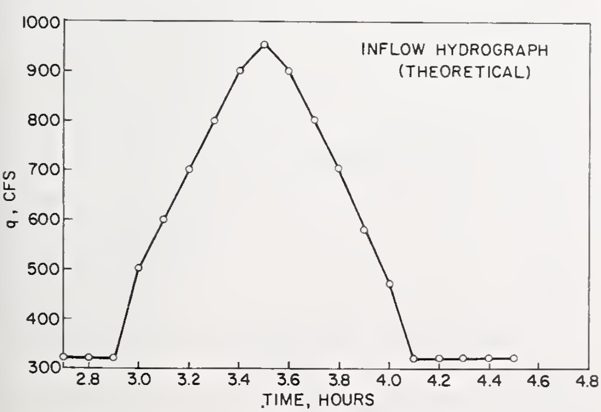

FIGURE 7.—Inflow hydrograph (theoretical).

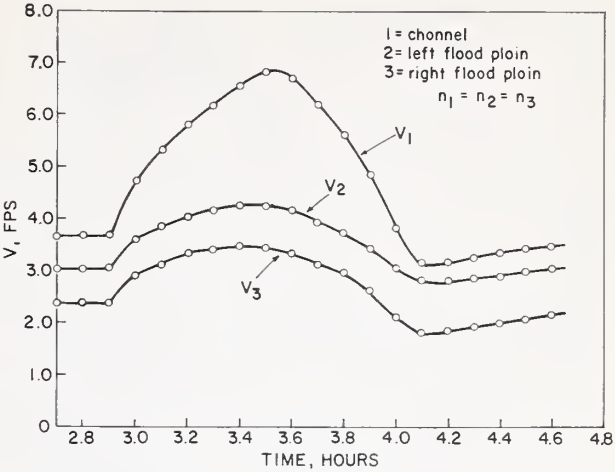

FIGURE 8.—Velocities at station 1, USDAHL 3-tube routing.

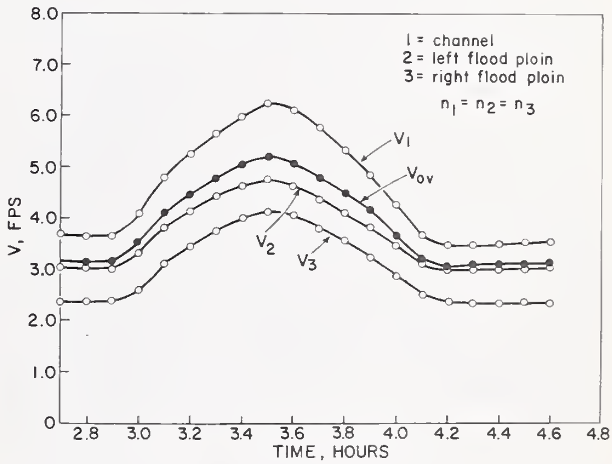

FIGURE 9.—Velocities at station 3, USDAHL 3-tube routing.

Figures 8–11 provide some idea of the drop in velocity as flow proceeds from the channel out

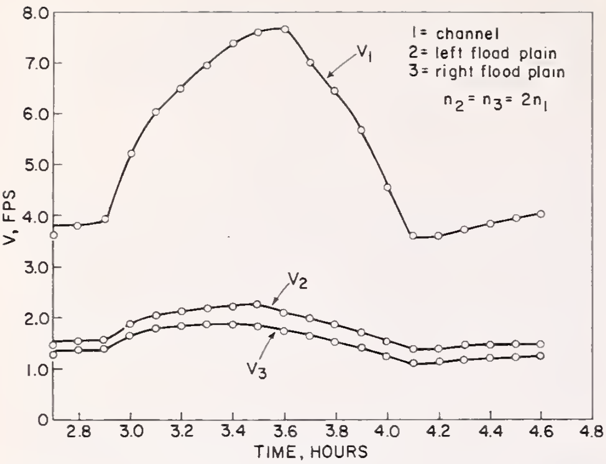

FIGURE 10.—Velocities at station 1, USDAHL 3-tube routing.

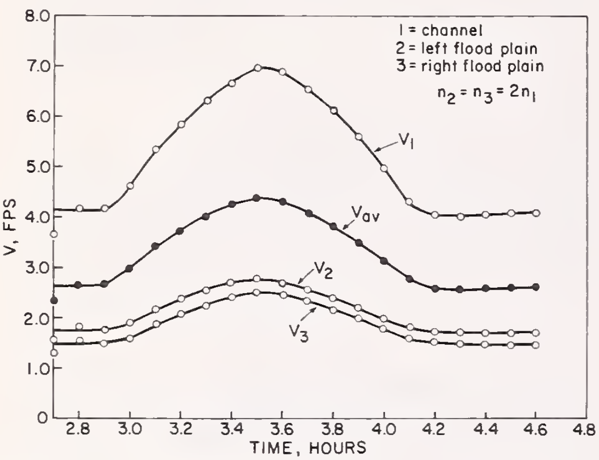

FIGURE 11.—Velocities at station 3, USDAHL 3-tube routing.

onto the flood plains. A drop in velocity signifies a drop in sediment-carrying capacity. Computations such as these can help us in the prediction of sediment deposition on flood plains.

Hydrographs of lateral flow from channel to flood plain and from flood plain to channel are given in figures 12 and 13 for stations 1 and 3. Again, the outflow from channel to flood plain is almost 10 times greater at station 1 because of greater proportions of the reach inflow hydrograph entering the channel. Some bridges and road dips at the inflow section to a reach would produce such a situation. Return flows from flood plains back to the channel are greatly diminished by longitudinal flows downstream on the flood plains. If there were a road embankment and a restricting bridge opening at station 3, return flow to the channel would account for all previous outflow. Again, the greater roughness of the flood plains in figures 14 and 15 increases the lateral flows out from the channel.

The flows plotted in figures 12–15 are in the units of cubic feet per second per foot of reach length. The distance between stations in this example is 2,000 ft. It is obvious, then, that the volumes of outflows from the higher velocities in the channel to the much lower velocities on the flood plains represent significant volumes over the total length of the reach. The drop in velocities (figs. 8–11) could account for a great quantity of sediment deposited over the length of flood plains. With more research, we may be able to develop a more precise system for predicting flood damages caused by sediment.

Hypothetical cases will be used to study computations of drops in velocities caused by in-

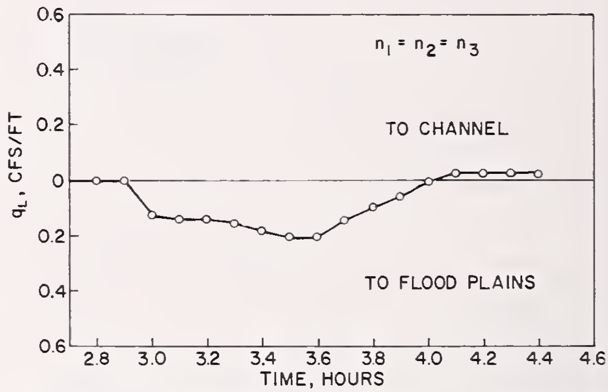

FIGURE 12.—Intertube flow at station 1, with equal roughness in all 3 tubes, USDAHL 3-tube routing.

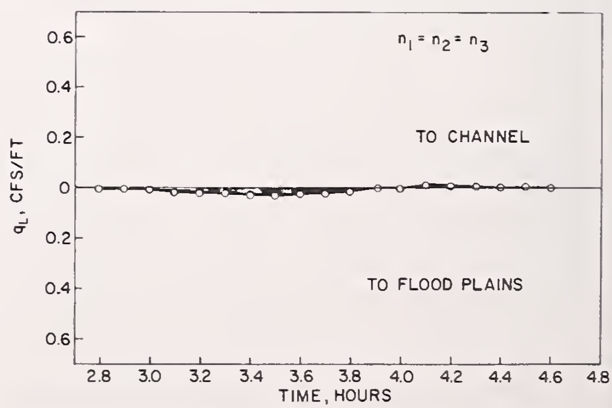

FIGURE 13.—Intertube flow at station 3, with equal roughness in all 3 tubes, USDAHL 3-tube routing.

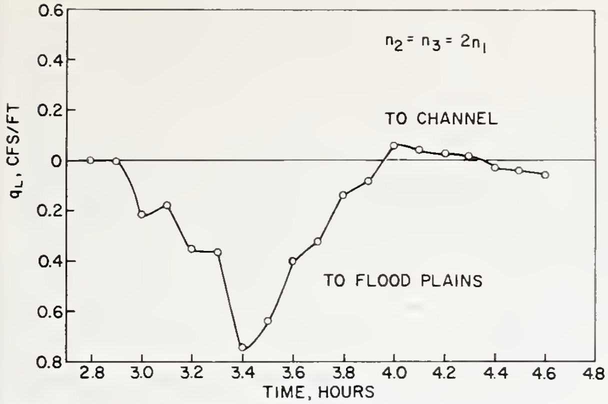

FIGURE 14.—Intertube flow at station 1, with channel roughness one-half that of flood plains, USDAHL 3-tube routing.

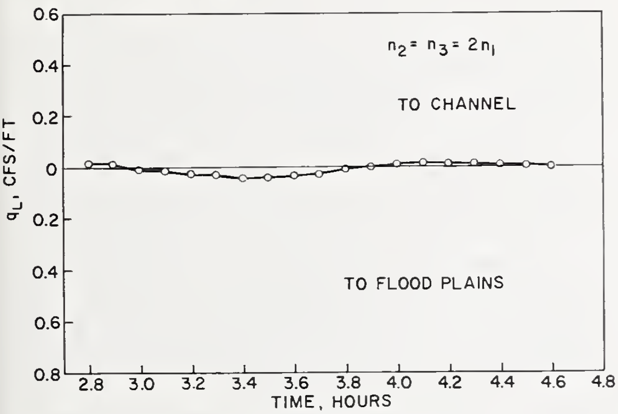

FIGURE 15.—Intertube flow at station 3, with channel roughness one-half that of flood plains, USDAHL 3-tube routing.

creasing roughness or decreasing gradients at downstream sections or by backwater from downstream control sections. We also hope to compute the increases or decreases in velocities at a given station as flow control shifts from one station to another with rising or falling stages.

Thus far, the USDAHL 3-tube model for routing flood flows is purely hypothetical, but field tests are planned under the cooperative study with the USDA Sedimentation Laboratory on Pigeon Roost Creek. The Sedimentation Lab has already furnished USDAHL a series of cross-section surveys for two reaches on Pigeon Roost Creek, together with several hydrographs of observed inflows and outflows. These data are being reduced and processed on punch cards in USDAHL for computer use by both labs. USDAHL is also planning a cooperative agreement with Howard University to conduct flume tests of the USDAHL 3-tube model in their laboratory.

We feel that casting off the usual constraint of maintaining a level water surface across each section liberates us to explore more fully the effects of variations between the flood plains and channel in respect to flow length, gradient, roughness, point of inflow, elevation, width, and cross-sectional area. Also, velocities and flow directions highly pertinent to the elutriation processes of sediment transport can be more precisely presented. At least, the challenge is too intriguing to ignore.

DEVELOPING A PARAMETRIC HYDROLOGIC MODEL USEFUL FOR SEDIMENT YIELD[1]

By W. M. Snyder[2]

INTRODUCTION

The parametric approach in hydrologic research is still evolving. A simple, rigorous definition acceptable to all is not available. Therefore, some discussion of the role and philosophy of the parametric approach is necessary before proceeding to development of a particular model. The relationship of the parametric approach to the deterministic and stochastic approaches must also be stated.

The reason for using the parametric approach is imperfect information. Sometimes the state of knowledge requires that we augment what we know with empirical information. When we attempt to quantify this empirical information rationally and systematically, we engage in parametric research. As an example, we can consider the permeability of a soil. There is not yet an exact and rigorous way to compute permeability from physical properties of the soil.[3] Permeability is quantified by measuring discharge and hydraulic gradient. It is the proportionality coefficient between these two measured quantities; therefore, it is a parametric quantity, not a deterministic one.

Frequently we know something about the system we are trying to model. Going back to our permeability example, from Darcy's law we obtain the linear relationship between hydraulic gradient and discharge from a saturated porous medium. But our information is imperfect in that we do not know the coefficient of the linear relationship for particular soils. Therefore, we resort to empirical calibration.

When we have perfect and complete information about a system, then we can construct deterministic models. For such systems, given an input, we can specify an exact output for any time or place without resorting to empirical information. When we have no information about a system, we cannot predict output. For this situation we can only regard the output as stochastic. A frequency curve of annual flood peaks is such a stochastic model. Rarely do we know all about a system. Also, rarely do we know absolutely nothing about a system. We might, therefore, regard determinism and stochasticism as boundaries to our information. Parametric procedures can be seen to lie between the deterministic and stochastic, and are a compromise of these two.

It must be kept in mind that different details of research purpose cover model development and model use. In model development we are concerned with formulation of concepts of physical processes and with quantification of the parameters specified in our formulated model. Naturally, we want a "best estimate" of our parameters based on available data. For this reason numerical optimization techniques are used in model development. We have all used least squares, for example, to fit a line to a set of data. The primary point to remember is that we search for values of our parameters.

In going from model development to model use, a shift is made from numerical analysis to numerical synthesis. Our purpose shifts from quantification of parameters to generating output from input. In other words, we simulate outputs by using our model of the system. Simulation with the model generally is for one of two purposes: to test the model or to predict for design purposes. If we simulate to test, we make the assumption that we still have something to learn about our model. What we learn through

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[1] Cooperative research of the Agricultural Research Service, U.S. Department of Agriculture, and the University of Georgia and Georgia Institute of Technology.

[2] Hydraulic engineer, Southeast Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, Athens, Ga. 30601.

[3] Hillel, D. 1971. Soil and water, physical principles and processes. 288 pp. Academic Press, New York.

simulation testing should feed back to new concepts in the model formulation. Full model development can therefore be seen to be a forward and backward oscillation between numerical analysis and numerical synthesis. Only when we reach some level of confidence do we consider applying the model for design prediction. It is the feedback between analysis and synthesis in parametric model development that will be explored in this paper.

MODEL BACKGROUND

The particular hydrologic model to be explored is designed to predict headwater hydrographs from input rainfall. By headwater hydrograph we mean the hydrograph of flow at any point in a basin where channel influence is not a significant feature. The model is made up of three components, a retention function, a characteristic function, and a state function.

Retention Function

The retention function serves to make the conversion from total rainfall input to a watershed to a quantity of rainfall effective in production of streamflow output. It is a substitute for an infiltration function and is used because there is not too much relationship between infiltration in a sprinkler plot and water retention in a complex real-world watershed of appreciable size. The retention function has been presented previously.[4] The use of the retention function allows generation of a total-flow hydrograph as total system response to input. There is no separation in the model into the fictitious hydrograph compartments of overland flow, subsurface flow, and ground-water flow. Infiltration is thus not applicable.

Characteristic Function

The characteristic function serves as a map of the watershed's potential to generate runoff. At present, the characteristic function is constructed as a time map rather than as an area map. That is, it measures timed potential of flow from the outflow point, rather than distance of potential of flow from the outflow point. The reason for the time potential is that characteristic functions were first derived from recorded hydrographs by an optimization process.[5] The computer program of the model standardizes the characteristic function to a volume equivalent to 1 watershed-inch.

State Function

The state function represents the wetness state of the watershed. It operates on the characteristic function to produce response functions. The state function varies during the progress of a storm and is a function both of rate of streamflow and of rate of rainfall input. Since the state function varies during the storm, its operation on the characteristic function produces highly variable response functions during the storm. A highly nonlinear system is thus modeled.[6]

Structure

Figure 1 is a schematic of the model. Rainfall is input as a series of time increments of storm rainfall. Parameters of the retention function, the characteristic function, and the state function are also input. Presently, there are 5 parameters in the retention function, 8 in the characteristic function, and 3 in the state function, for a total of 16. It appears that several of these parameters have only slight influence on the generated hydrograph, and it should be possible to reduce the number to about 12 parameters.

The retention function is evaluated at each time corresponding to the times of the rainfall increments. Average values of the function for

[4] Snyder, W. M. 1971. A proposed watershed retention function. Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers 97 (IR1): 193–201.

[5] Snyder, W. M., Mills, W. C., and Stephens, J. C. 1970. A method of derivation of non-constant watersheds response function. Water Resources Research 6 (1): 261–274.

[6] Snyder, W. M., and Asmussen, L. E. 1972. Subsurface hydrograph analysis by convolution. Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers 98 (IR3): 405–418.

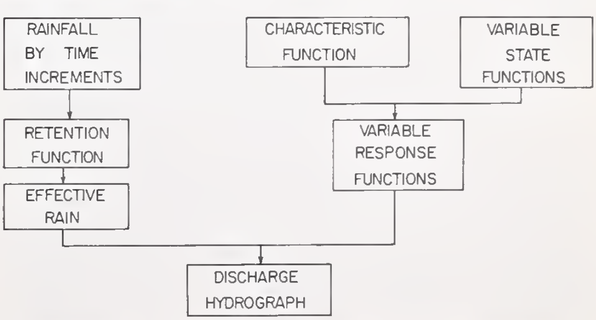

FIGURE 1.—Schematic of storm hydrograph model.

each time increment are then subtracted from the rainfall. Amounts greater than retention are called effective rain increments.

The state function is evaluated for each period of rain. Since the function is dependent on both streamflow and rainfall during the period, the function takes on different values for each period. Each of the evaluated state functions is then convolved with the characteristic function to produce a response function for each period of rain. The response functions for each period are different, since the state functions producing them are different.

In a second stage of convolution the effective rain is convolved with the variable response functions to generate the outflow hydrographs.

GENERATED HYDROGRAPHS

A computer program of the hydrograph model shown schematically in fig. 1 was first tested by simulating hydrographs of hypothetical drainage areas ranging from 0.01 acre to 100 mi^2 to establish the program's accuracy and flexibility and its response to changes in the various parameters. No attempt was made at this stage of development to match recorded hydrographs. Such testing has been done in later work. Working ranges of the parameters were known, since all components of the model had been previously derived from data by analytical programs.

Figures 2, 3, 4, and 5 show simulated storm hydrographs for a hypothetical 10-mi^2 drainage area. On all figures, rainfall, retention, and effective rainfall are shown at the upper left, and the generated discharge hydrograph is shown at the lower left. The characteristic function and

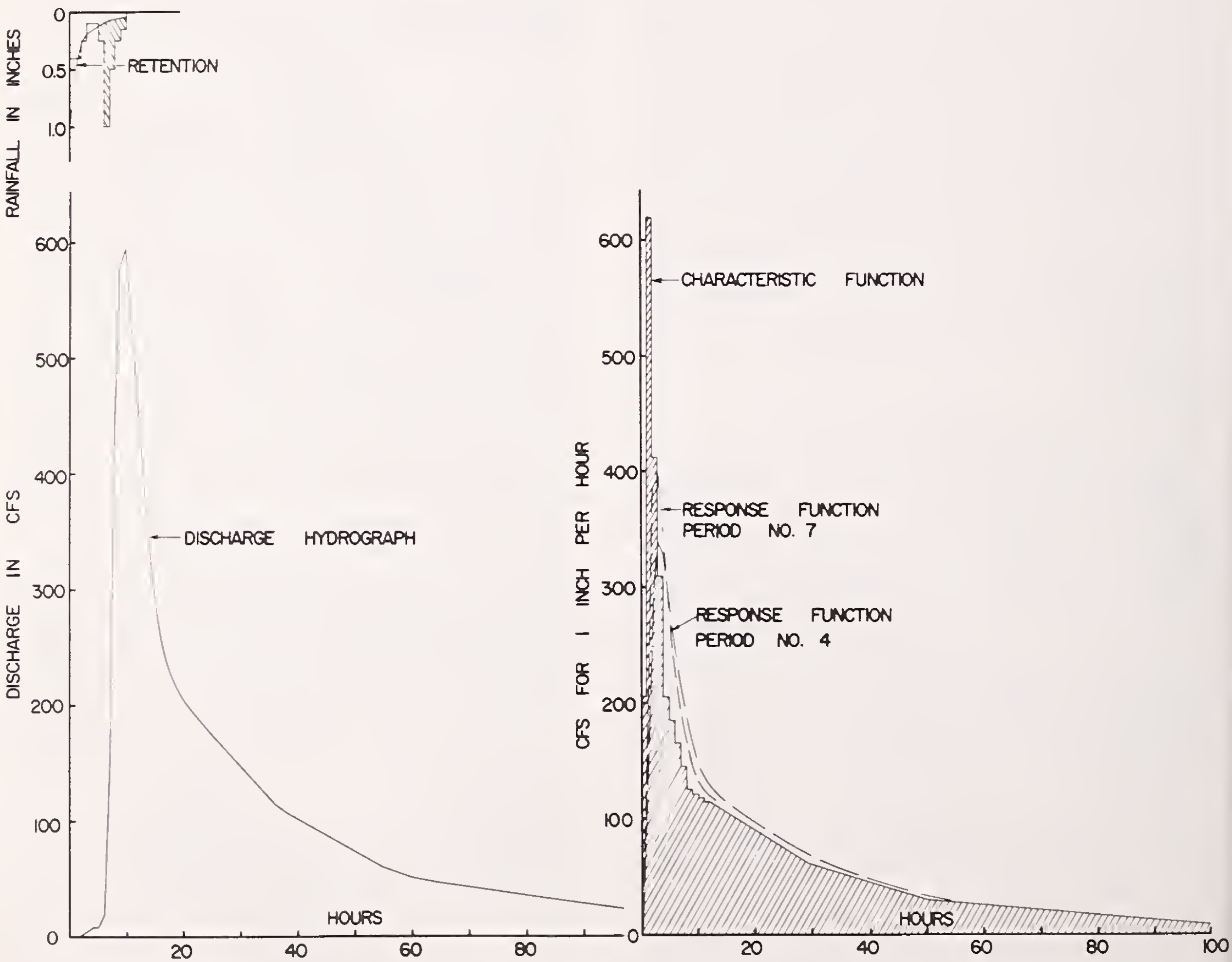

FIGURE 2.—Simulation on 10 mi^2 with high initial retention.

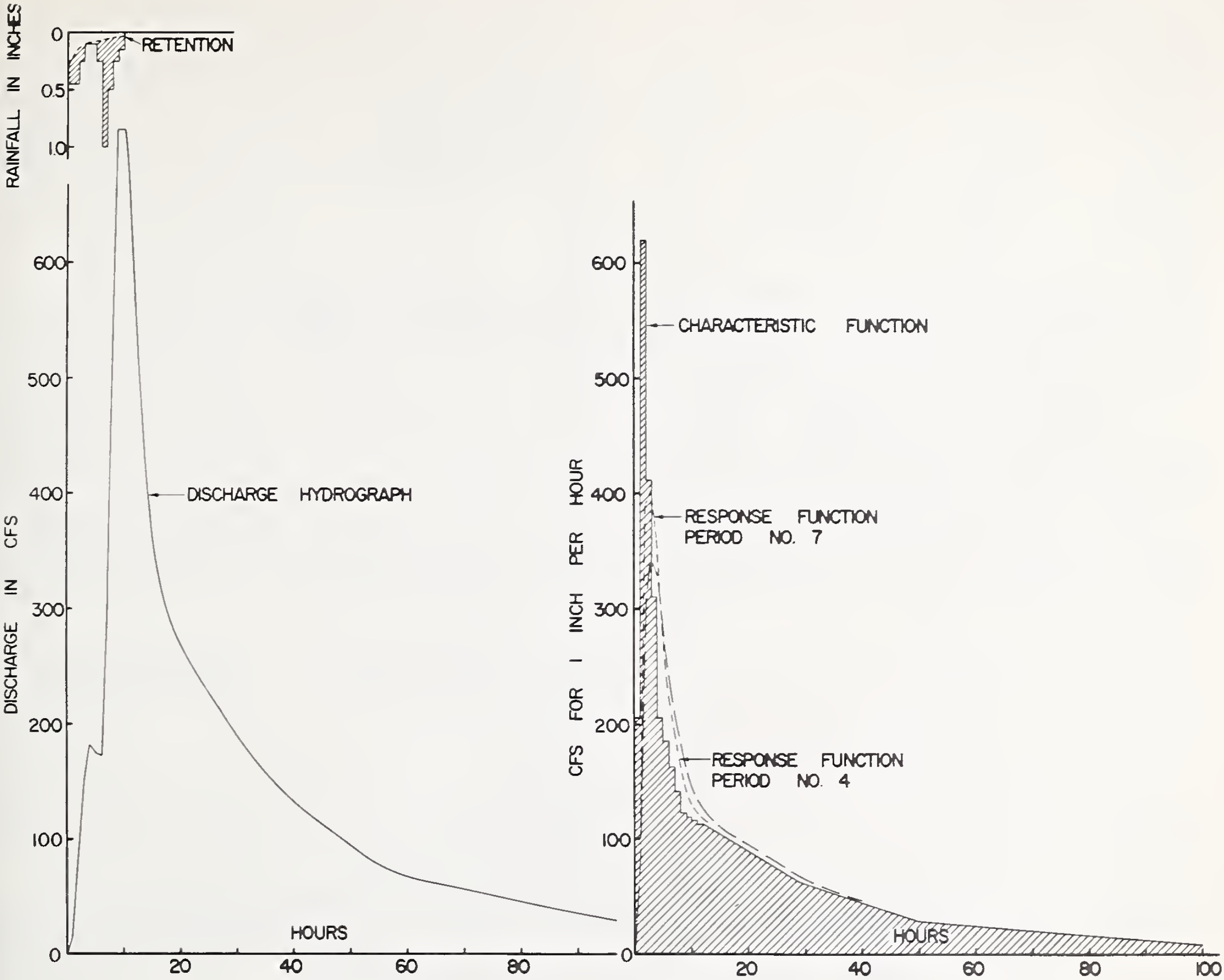

FIGURE 3.—Simulation on 10 mi² with low initial retention.

selected response functions are shown to the right. In figure 2 the retention is initially high. The watershed response is not highly nonlinear since response functions for rainfall periods 4 and 7, as examples, are not greatly different. The generated hydrograph had a peak of nearly 600 ft^3/s.

Figure 3 shows the same storm for the same drainage area with a lower initial rate of retention than used in figure 2. Response is still nearly linear. However, the larger volume of effective rain produced a hydrograph peak larger than 700 ft^3/s.

In figure 4, the same retention is used as in figure 3. The characteristic function is the same. However, the state function was changed so that it produced a more sluggish response. The unit response functions have appreciably lower peaks than previously and the response for rainfall period 4 is now substantially less than for period 7. The peak of the discharge hydrograph has been reduced to just over 600 ft^3/s. This reduced peak is compensated by increased flow during the recession portion of the hydrograph.

Figure 5 shows the effect of a change in the state function to produce highly nonlinear response. The unit response function for rainfall period 7 has its peak increased to about 460 ft^3/s, compared to about 220 ft^3/s for rainfall period 4. The effect on the generated hydrograph is to increase the peak flow rate to about 740 ft^3/s.

In summary, figures 2, 3, 4, and 5 show outflow hydrographs for one rainfall pattern on one watershed. The characteristic function was held constant. Only the initial rate of retention and the routing to outflow by the state function were changed. It is evident that the changes in the hydrograph produced by these parametric

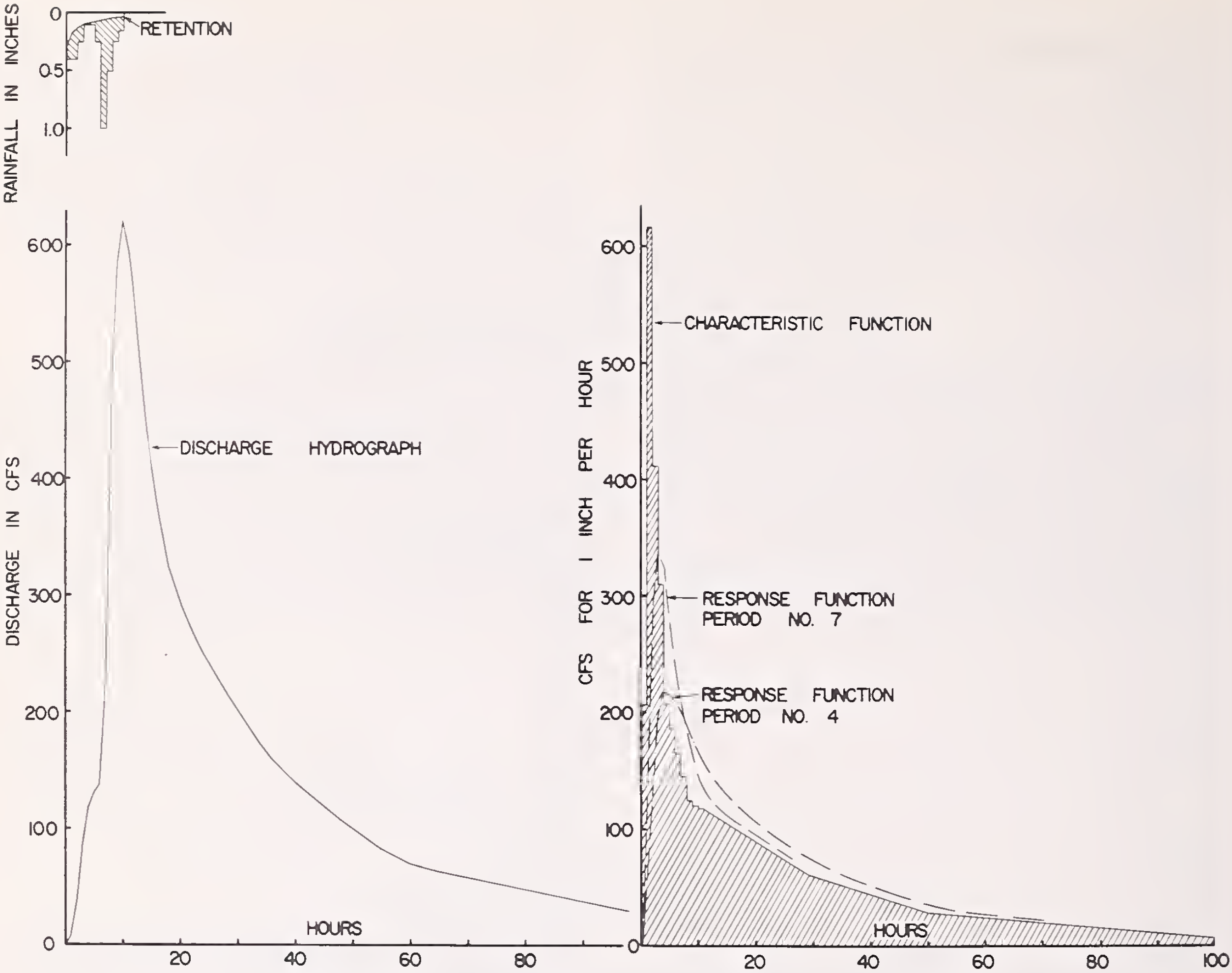

FIGURE 4.—Simulation on 10 mi² wtih sluggish state function.

changes, plus all the additional changes possible through changed characteristic and retention parameters, portray a model of simple structure yet extreme flexibility sufficient to fit any conceivable hydrograph.

The range of the model is shown by figures 6 and 7. Figure 6 is the hydrograph for 100 mi². Comparison of the characteristic function with the response functions shows that this figure represents some flashy watershed with little attenuation by routing to the watershed outlet. Note that the base of the hydrograph is 160 h with a time increment of 2 h. The peak discharge is 15,500 ft³/s.

Figure 7 shows outflow from a plot of 0.01 acre. The response functions show that flow is sluggish in relation to the characteristic function. We might visualize this plot as a sandbox with only interflow and no surface runoff. Peak outflow is only 0.016 ft³/s. Note that the time base covers only 0.8 h in 0.01-h time increments. It is doubtful whether such rainfall data exist, but the model can handle this time scale of input and output.

SYSTEMATIC LEARNING

Model development is a learning process involving both structural concepts and parametric quantification. Since the simulation of hydrographs indicates that the model structure is adequate and flexible and no structural changes are indicated, the next concern is the quantification of the parameters. To arrive at a set of parametric values common to both analysis and synthesis procedures requires a common objective, which must be stated in terms of the degree to which a generated hydrograph fits historical hydrographs. One such objective is to require

the sum of squares of the differences between ordinates of the generated and observed hydrographs to be a minimum. This is the customary requirement of least-squares fitting. However, the means of arriving at this optimum of least-square error, common to both analysis and synthesis, is not self-evident.

Trial-and-Error Procedures

It is theoretically possible to try various values of the model parameters and choose the best set of the values tried. Practically, however, this trial-and-error scheme is quite impossible, as illustrated by the number of tries that must be made in order to examine all possible combinations to find the discrete minimum (table 1).

Consider searching across three levels of a parameter to find which one of these three provides the best fit to a particular recorded hydrograph. We would arbitrarily set the parameter high, middle, and low in its anticipated range. Three simulation runs are required. Now consider searching across three levels of a second parameter. We do not know which combination of the three levels of the two parameters would yield the best fit. Therefore, for each of the three levels of the first parameter we would need three trials on the second, a total of nine runs. For three levels of three parameters, 27 runs

TABLE 1.—*Combinations of* L^p

No. of parameters	Number of levels		
	3	4	5
5	2.4×10^2	1.0×10^3	3.1×10^3
10	5.9×10^4	1.0×10^6	9.8×10^6
15	1.4×10^6	1.1×10^9	3.1×10^{10}
20	3.5×10^9	1.1×10^{12}	9.5×10^{13}

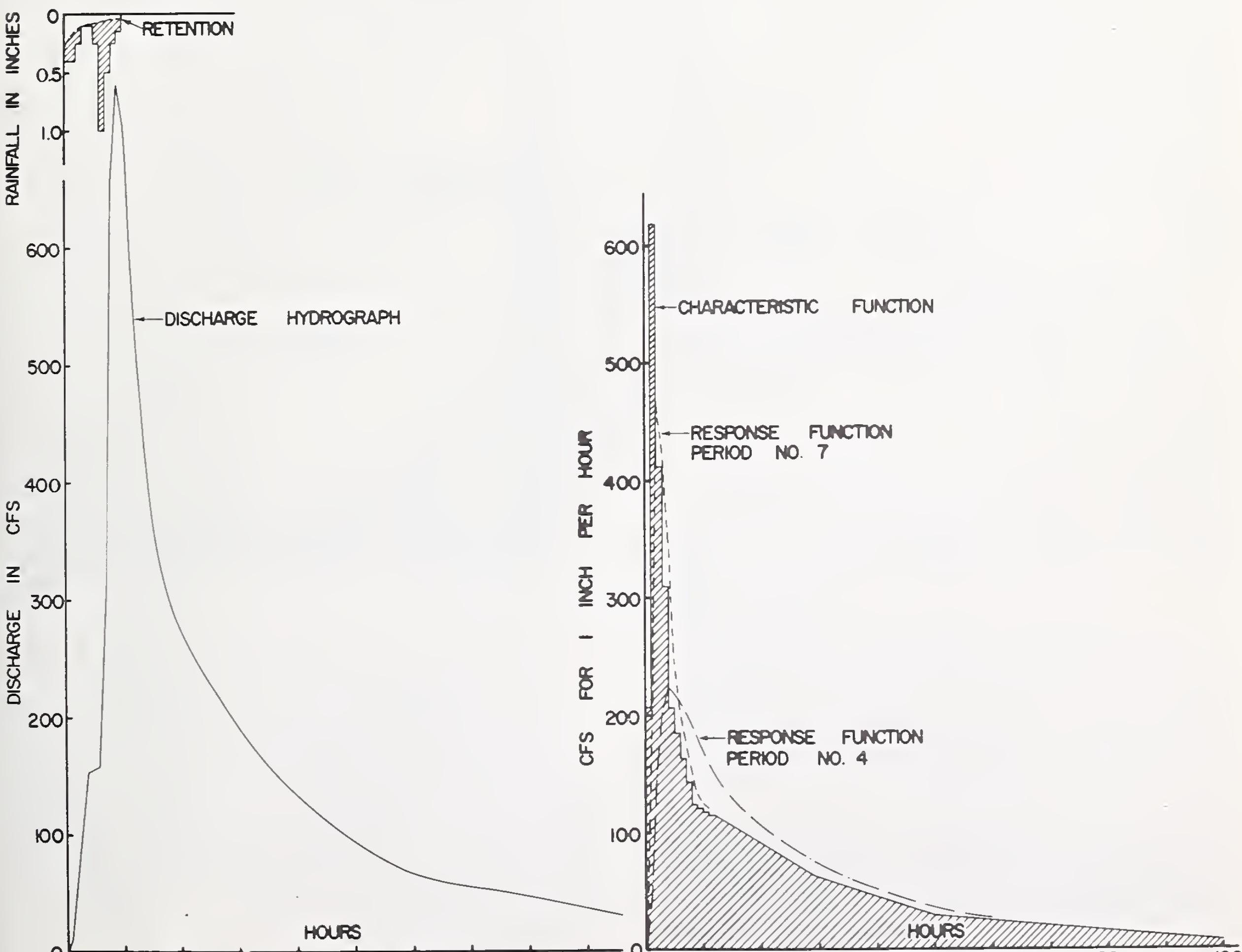

FIGURE 5.—Simulation on 10 mi² with highly nonlinear state function.

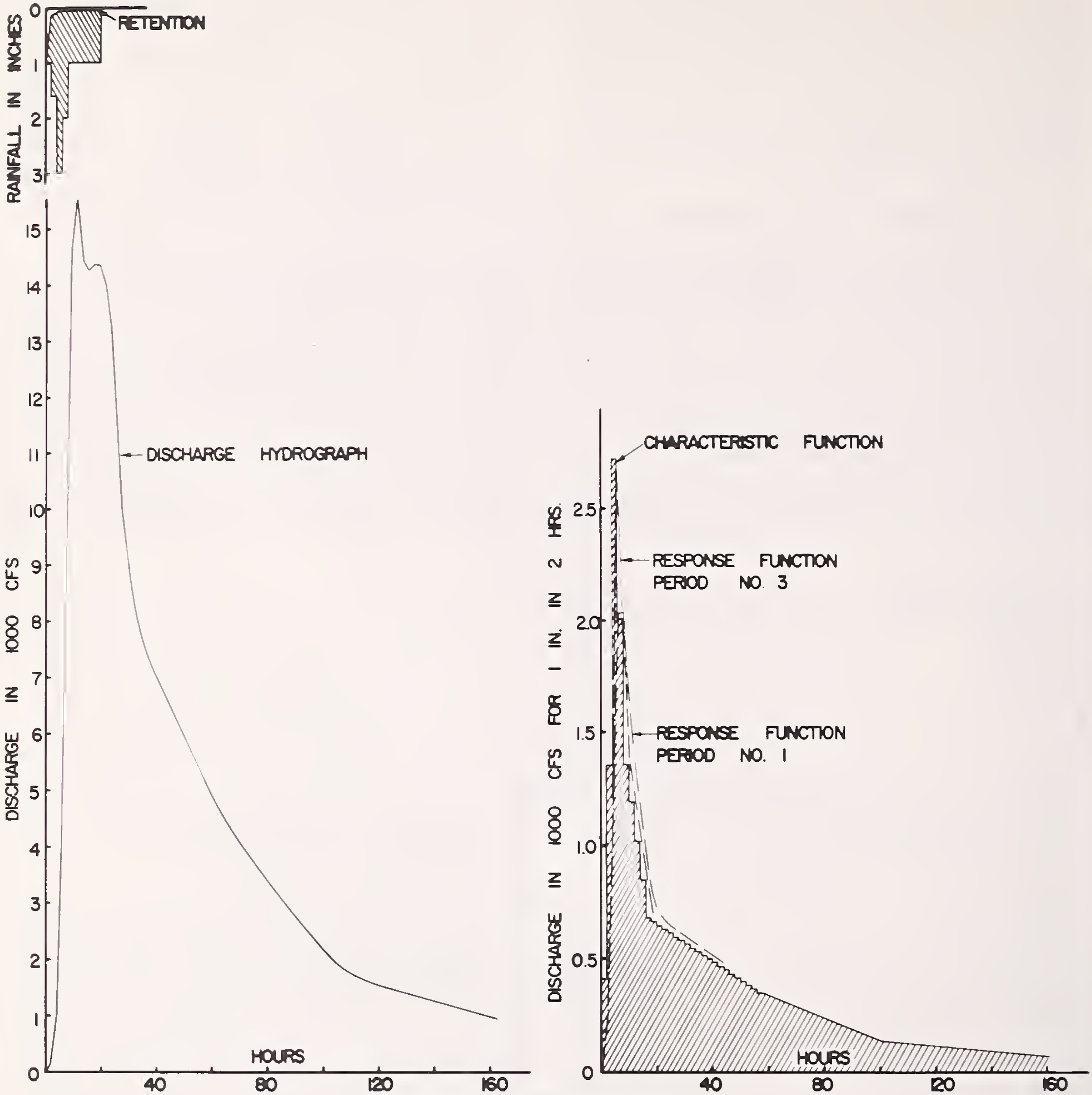

FIGURE 6.—Simulation on 100 mi².

would be required to search all combinations. It may be noted that the number of combinations is given by L^p, where L specifies the number of levels of search for each parameter, and P is the number of parameters.

Table 1 shows that for any practical number of parameters and levels of search the number of combinations (hence the number of simulation runs) becomes fantastically large. We simply can't afford this computer time, and other optimization methods are required.

Parameter Evaluation in Analysis

In the early phases of development, hydrologic model components were derived by fitting the model to historical data by nonlinear least squares. This method is an iterative technique. The linear differential correction equation (equation 1) is solved repeatedly by least squares until all parameter corrections fall below some preset small value.

$$E=Q-\widehat{Q}=\frac{\widehat{Q_1}-\widehat{Q}}{\Delta p_1}dp_1+\frac{\widehat{Q_2}-\widehat{Q}}{\Delta p_2}dp_2+\ldots. \quad (1)$$

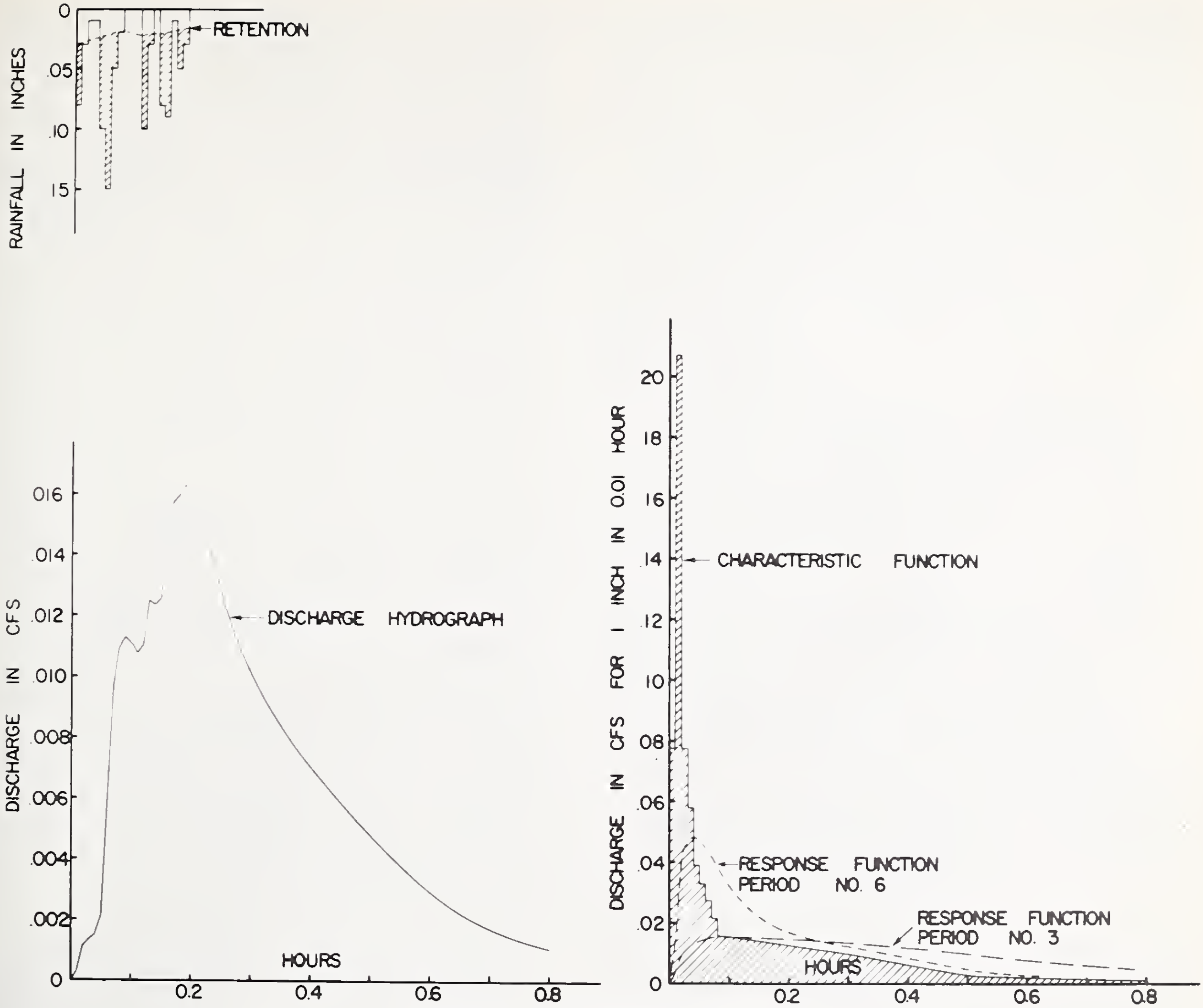

FIGURE 7.—Simulation on 0.01 acre.

In equation 1, E is the error between an observed hydrograph ordinate Q and the model-predicted ordinate $\widehat{Q}$. This prediction is based on some initial set of model parameters. $\widehat{Q}_1$ is the model-predicted ordinate with parameter number 1 incremented by Δp_1. $\widehat{Q}_2$ is the model-predicted ordinate with parameter 2 increased by Δp_2. The ratios $(\widehat{Q}_i—\widehat{Q})/\Delta p_i$ are approximations to the first derivatives of the function for Q with respect to any parameter p_i. We can regard E as the "y" and the ratios as the "x's" of a multiple linear regression equation. By applying the equation, as in ordinary least squares, to a data set consisting of the errors and the ratios for each ordinate of a storm hydrograph, we can compute the dp_i terms as regression coefficients. These dp_i values are corrections to the initial values of the parameters. By adding the corrections to the initial values, new values of $\widehat{Q}$ and $\widehat{Q}_i$ are obtained. Continuation leads to repeated evaluation of equation 1 until the dp_i's become so small that little further adjustment of the errors $Q—\widehat{Q}$ is possible. Then the values of the parameters are considered optimum.

Parameter Evaluation in Synthesis

In order to develop a systematic body of information about the parameters of our model, we should be able to adjust the values of parameters during synthesis of storms as well as during analysis of recorded storm hydrographs. What is more, we should use an identical basis for adjustment and not rely on some subjective appearance of correspondence between the predicted and observed.

The computer program of the model can calcu-

late ratios $(\hat{Q}_i - Q)/\Delta p_i$. For each simulation run these ratios are computed for every ordinate by incrementing each parameter in turn by some small amount Δp_i. In the modern terminology of systems analysis these partial derivatives are called sensitivity coefficients. They give the amount by which a unit change in the parameter would change the model-predicted ordinate.

Figure 8 shows the sensitivity coefficients for the simulated hydrograph plotted in figure 5. Figure 9 shows the sensitivity coefficients for the hydrograph for the 0.01-acre drainage area given in figure 7. The two sets of coefficients are

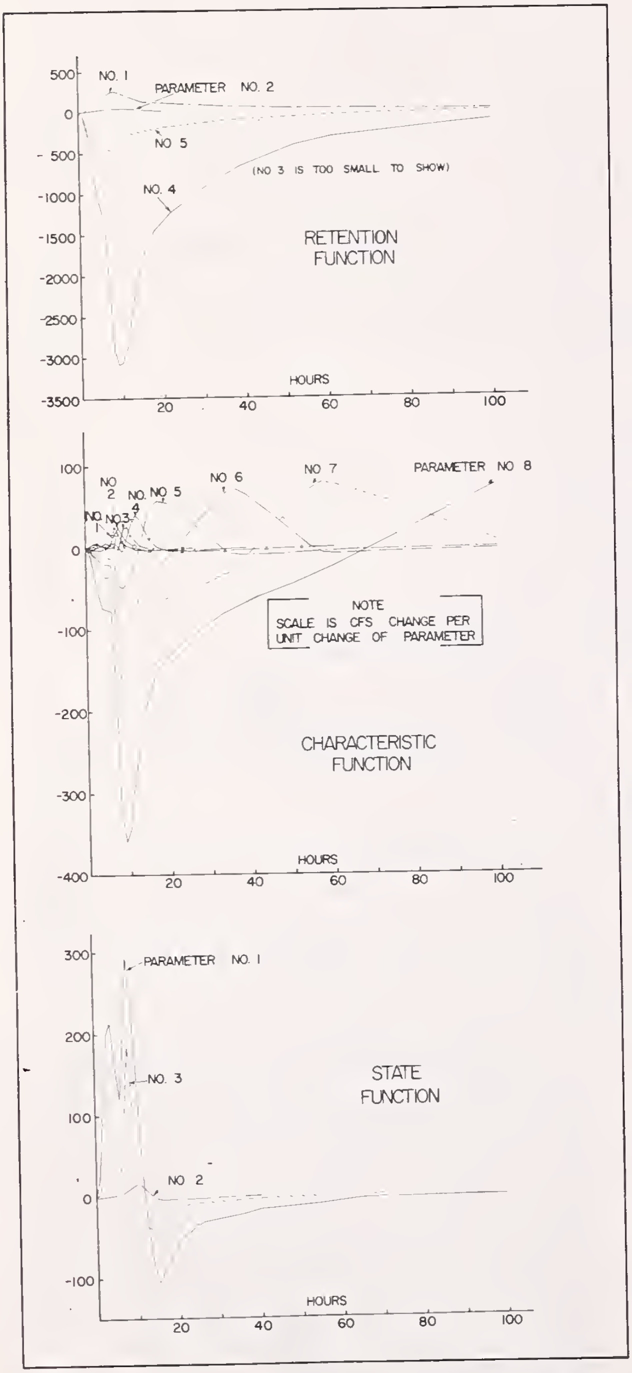

FIGURE 8.—Sensitivity coefficients for simulation on 10 mi².

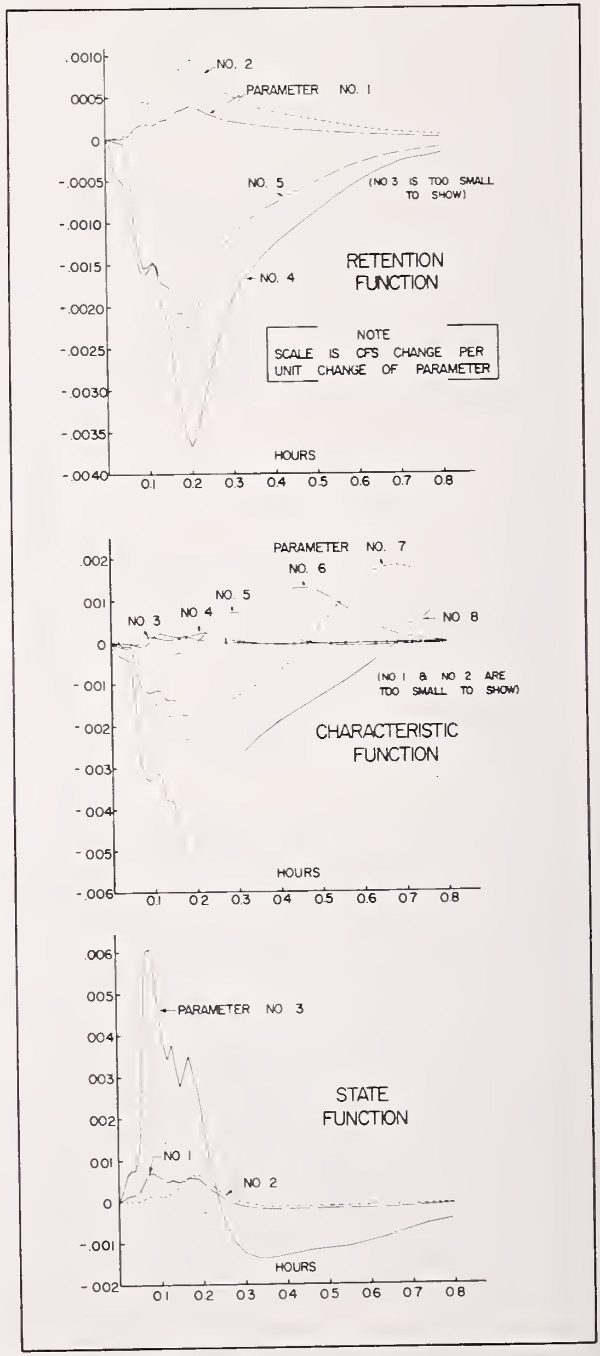

FIGURE 9.—Sensitivity coefficients for simulation on 0.01 acre.

completely different in scale, reflecting the difference in magnitude of flows from the two hypothetical areas. Similar patterns are present in the two sets of coefficients. These patterns indicate the nature of adjustment to the hydrograph caused by a positive unit change in the parameter.

Changes in the retention function parameters have the effect of increasing or decreasing the total storm hydrograph. The change is in the same direction, all positive or all negative, from the point of rise, across the peak, and through the recession. Parameters 4 and 5 predominate. Parameter 4 expresses the final (wet) retention rate. Parameter 5 is the initial retention rate. Parameters 1 and 2 are mathematical shape parameters and have lesser effect. Parameter 3 expresses a maximum retention rate and has insignificant effect on the generated hydrograph.

Changes in the parameters of the characteristic function (ordinates of the function at selected points in time) produce both positive and negative changes in the hydrograph. All ordinates at intermediate times are computed by linear interpolation. In figures 8 and 9, the sensitivity coefficients for the characteristic function are positive at the selected ordinate locations, and negative at points somewhat removed. The negative coefficients result because the total characteristic function is always rescaled to one watershed-inch. Changes in the recession component of characteristic function are predominant.

The sensitivity coefficients for the state function show that it concentrates change during the rising and crest times of the generated hydrograph, with lesser change during the recession. The state function shapes the response functions, and these produce greatest effect early in the storm hydrograph.

If one is trying to fit a generated hydrograph to an observed hydrograph, the sensitivity coefficients can be used as follows. The differences between the generated discharges and the observed discharges form an error set running from beginning to end of the storm. This error set can be visually correlated with one or more sensitivity coefficient patterns such as shown in figures 8 and 9. The adjustment of one or more of the parameters is thereby indicated. Certainly this process is subjective and crude compared to adjustment of all parameters simultaneously by nonlinear least squares. Nevertheless, this crude process is the synthesis analogy to the more powerful analytic learning process of optimization.

ADAPTATION TO UNGAGED DRAINAGES

We have shown the current stage of development of our parametric hydrograph model. Particularly, we have shown that the analysis and synthesis computer programs are designed to develop systematically more information about the numerical values of the parameters. We must recognize, however, that all this additional information is based on historical data. The problem of how to estimate the parameters for a drainage area where we have no recorded hydrographs is now being attacked. Only when we achieve a satisfactory answer to this problem will we have reached full development of the model.

Many previous attempts at linking model parameters to watershed characteristics have been based on statistical correlation. We are hoping to include considerable deterministic procedure in estimation of model parameters. This will be possible because the three model components are rational analogs to physical watershed processes. The retention function is a composite of infiltration capacity, surface and profile water storage capacity, and initial amount of stored water. The characteristic function is a map of runoff potential, which can be estimated by physically mapping or sampling the watershed for such features as soil depth and permeability. The routing function has received less attention to date. This function, we hope, will express the dynamic features of flow paths through the profile and stream channels to the outlets.

MODEL FEATURES USEFUL FOR SEDIMENT-YIELD COMPUTATION

Computation of sediment yield is here taken to mean estimation of sediment loads for drainage areas with little or no hydrologic or sediment record. This estimation will require construction and calibration of a sediment-yield model. Since water and sediment runoff are inextricably

intertwined, the structures of each model must reflect features and needs of the other. The hydrograph model should be structured with the practicalities of sediment-yield prediction in mind. The sediment portion of the model should reflect the practical state of the art of hydrologic forecasting. Stated another way, there is little purpose to a highly precise and theoretical sediment model if transport is based in part on a crude hydrograph model. Both models should be based on similar types and similar quality of data describing the drainage area.

Several features of our parametric hydrograph model appear useful in sediment-yield computation. The hydrograph model is simple, being structured on only 16 parameters grouped into 3 components, yet it is highly flexible. For example, through appropriate parameter values it can reflect changes in land use and management. The changes can be reflected in both the volume and rate of runoff. Since runoff rate is one of the controls on rate of sediment transport, the flexibility of the model makes it potentially useful in predicting hydrologic and sediment consequences of alternative watershed management programs.

The characteristic function in the hydrograph model was described as a map of runoff potential of the watershed. We hope to construct this functional representation of the watershed through physical mapping or sampling. It is speculated that an erosion characteristic, a map of likely sediment sources, can also be defined. There must be a strong similarity between a runoff map and an erosion map of a watershed. Both should be determinable through very similar mapping procedures.

The state function is the hydrograph model component which moves or routes the water to the outlet. The state function operates on the characteristic function to produce variable response functions. An analogous routing function to move the erosion characteristic function to the outlet may be possible of definition. Present knowledge of sediment transport through hydraulic channels would play a role in the development of such watershed sediment models.

The operation of the state function on the characteristic function to produce variable response functions is a first-stage convolution. In a second stage the variable response functions are convolved with the effective rainfall to generate the hydrograph. The hydrograph is thus the sum of pulses of flow. Each runoff pulse comes from a time increment of rainfall and each pulse depends on the intensity of rain in that time increment, and on the state of the watershed in that time increment. The mathematical process of convolution carries these pulses through the system. The characteristics of the separate pulses are not averaged and lost in the postulated reservoir of a routing-type model. Sediment production should also be pulsating, showing the ability of the individual bursts of rainfall to scour and transport sediment.

Several similarities of origin and transport of water and sediment in a watershed have been discussed. The parametric model appears to be a simple and practical yet adequate analogy to the physical processes of water movement. Hopefully, analogous development of components for a sediment-yield model will bring about a happy marriage of the water and sediment portions of a total prediction scheme.

AN ATTEMPT TO PREDICT CHANNEL SEDIMENT-TRANSPORT CAPACITY WITH SIMILITUDE PRINCIPLES

By Neil L. Coleman, G. C. Bolton, and A. J. Bowie[1]

INTRODUCTION

Among the many problems in the general area of sediment-yield studies, there are two very difficult ones having to do with channels. The first of these problems is the direct and accurate measurement of the sediment-transport rate in a channel in the field; the second problem is obtaining a general understanding of the fluid mechanics of sediment transport so that sediment-transport rates can be predicted.

The practical problem of transport-rate measurement has been attacked by the development of special structures for measuring total sediment load (*5*)[2] or by taking advantage of natural situations where total sediment load presumably could be measured (*4*). A comprehensive study of this type was undertaken by Bowie et al. (*3*), who carried out sediment-transport measurements at a specially constructed measuring station on a small alluvial channel in the Pigeon Roost watershed in Marshall County, Miss.

Attempts to understand the fluid mechanics of sediment transport have generally proceeded from flume experiments. These experiments have usually given results that are internally consistent; however, agreement between the results of one worker and another has been obtained only through the application of similitude principles (*1,2,11*).

Willis and Coleman (*11*) produced a unified correlation of sand transport and flow data from flume experiments performed by several workers under diverse conditions. This correlation was obtained by the use of nondimensional terms generated by applying a normalization technique (*6*) to the equations of state, continuity, and motion for a sediment-water mixture. The resulting similitude terms were the familiar Reynolds and Froude numbers and a sand-transport similitude number. A boundary condition parameter incorporating the effects of water temperature and particle size was also formulated.

The experimentally determined relations between the above similitude terms constitute solutions to the equation of motion for a sediment-water mixture. This paper describes an attempt to use these relations, based on similitude theory and laboratory experiments under steady-flow conditions, to predict the sediment-transport rates that were actually observed in the field study of Bowie et al. during typical intermittent runoff events.

The field measurements of Bowie et al. (*3*) were carried out at the facility shown in figure 1. The installation consists of an alluvial channel containing a normal section at which flow properties, such as width and depth of flow, can be measured. Downstream is a sheet pile control structure that serves as a flowmeter. As illustrated in figure 2, the control structure provides

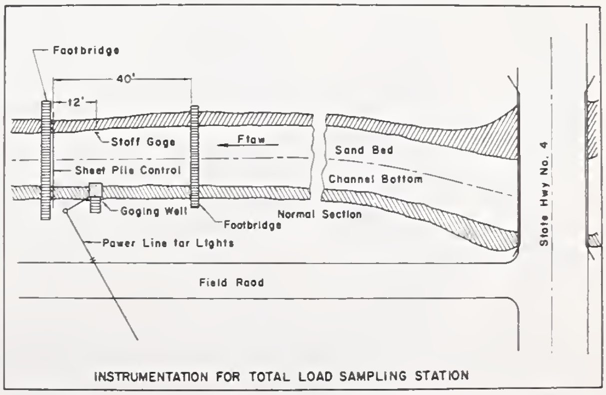

FIGURE 1.—Plan view of the total-load-measuring station. (After Bowie et al., *3*.)

[1] Geologist, mathematician, and hydraulic engineer, respectively, USDA Sedimentation Laboratory, Southern Region, Agricultural Research Service, Oxford, Miss. 38655.

[2] Italic numbers in parentheses refer to items in "Literature Cited" preceding the appendix to this paper.

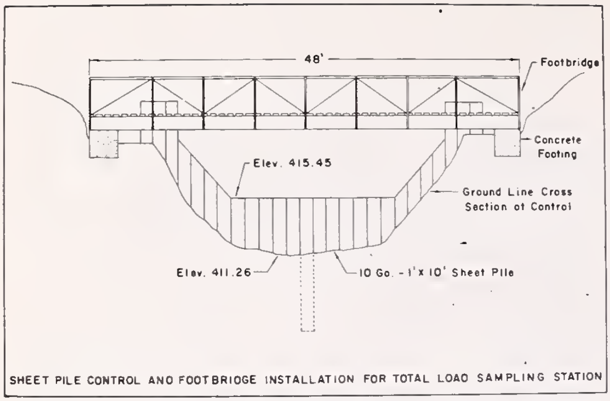

FIGURE 2.—The sheet pile control structure. (After Bowie et al., *3*.)

about 4 ft of free overfall, which can be sampled with a DH-48 sediment sampler to determine the total sediment load.

From December 28, 1966, through February 21, 1971, 367 measurements of total sediment load were made, with concurrent observations of discharge, water temperature, and depth of flow at the normal section. As in any field study, the program was complicated by the varying frequencies of opportunities to make measurements in any one particular discharge. As shown in figure 3, the population of observations was strongly biased in favor of the lower discharges.

It has long been recognized (*9*) that the sediment-transport rate in a channel is subject to turbulent fluctuation and other changes of a stochastic nature even under steady conditions of discharge, flow depth, and water temperature. Figure 4 illustrates these effects as they were experienced in the field study.

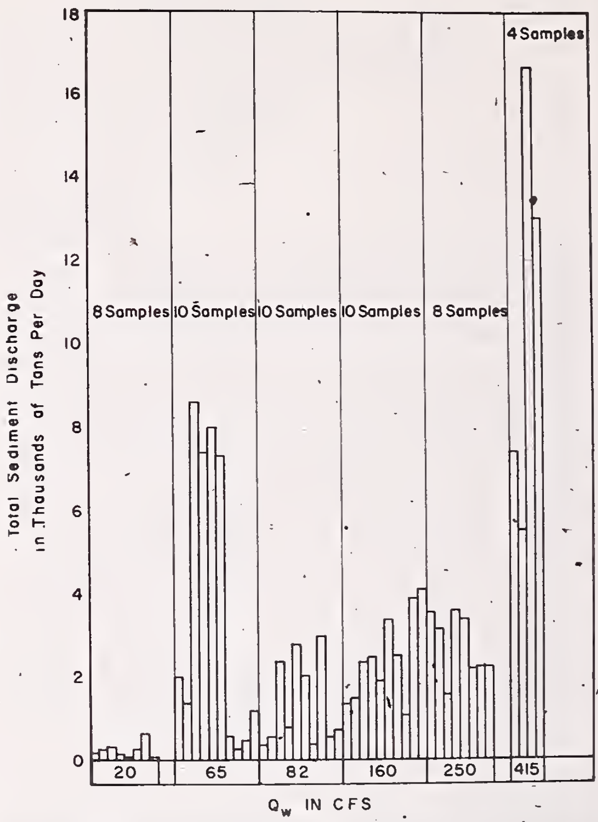

FIGURE 4.—The variability of sediment-transport rate measurements made during the field study.

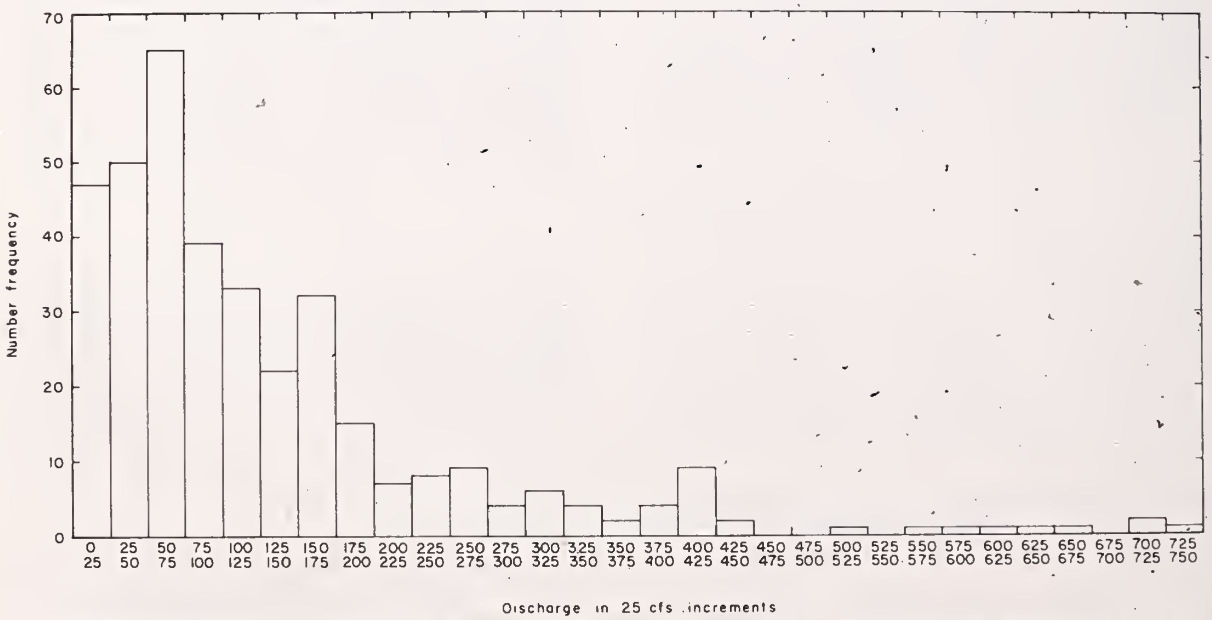

FIGURE 3.—Number frequencies of observed discharges, December 28, 1966, through February 21, 1971.

SIMILITUDE OF SEDIMENT TRANSPORT

The sediment transport similitude number has been defined by Willis and Coleman (*11*) as

$$A_L = \frac{\rho_s - \rho_w}{\rho_w} \cdot \frac{L}{\rho_s g Y U}, \tag{1}$$

where L=the total load in pounds per second per foot of channel width,
ρ_s, ρ_w=the sediment and water densities, respectively,
g=the gravity field strength,
Y=flow depth,
and U=the mean flow velocity.

This similitude term has been found to correlate with the Froude number,

$$F = \frac{U}{\sqrt{gY}}, \tag{2}$$

and with the boundary condition similitude number,

$$D = \frac{g^{1/3} d}{\nu^{2/3}}, \tag{3}$$

where ν=the kinematic viscosity of the water in the channel,
and d=the median particle diameter of the channel-bed material.

The basic equation of sediment transport is therefore

$$L = A_L \left(\frac{\rho_s \rho_w}{\rho_s - \rho_w} \right) g Y U, \tag{4}$$

where A_L indicates the function of F and D determined from flume experiments.

A graph of this function is given in figure 5, which applies to the transportation of sand-size material, regardless of whether it is being moved in suspension or as bedload. The data sources used in producing figure 5 are listed in table 1, as are the ranges of data used.

TABLE 1.—*Sources and general ranges of data used*[1]

Data source	Flume dimensions (ft)	Particle size (mm)	Depth range (ft)	Velocity range (ft/s)	Temperature range (° F)
Willis and Coleman	100 by 4	0.10	0.64 –1.10	1.17–5.16	64–89
Franco (1968)	75 by 3	.23	.422– .521	1.48–1.20	40–80
Guy et al. (1966)	150 by 8	.19	.49 –1.09	1.04–4.74	54–67
		.27	.45 –1.13	.79–4.93	50–65
		.28	.30 –1.07	.82–4.93	50–62
		.45	.19 –1.00	.65–6.18	48–68
Do	60 by 2	.32	.51 – .74	.86–5.73	44–94
		.33	.49 – .52	1.02–5.93	67–68
		[2].33	.48 – .53	1.06–6.34	65–75
		.54	.59 – .88	.89–6.27	60–77
Stein (1965)	100 by 4	.40	.32 –1.20	1.38–5.42	68–84
Kennedy (1961a)	40 by .88	.233	.147– .346	1.57–3.42	76–86
	60 by 2.8	.233	.145– .348	1.35–3.45	73–81
	40 by .88	.549	.074– .346	1.65–4.65	76–82
Kennedy (1961b)	60 by 2.8	.145	.228– .550	.91–2.21	65–78
Vanoni and Brooks (1957)	60 by 2.8	.145	.203– .553	.77–2.53	62–81
Nomicos (1956)	40 by .88	.091	.244– .284	1.23–2.32	[3]77
		.137	.233– .243	1.38–2.13	75–76
		.145	.241– .242	.91–2.06	[3]77
		.148	.253– .255	2.28–2.29	[3]77
		.152	[3].241	.80–2.66	77–79
Barton and Lin (1955)	70 by 4	.18	.30 –1.38	.71–3.60	66–80
Brooks (1955)	40 by .88	.10	.17 – .284	.82–2.13	[3]77
		.16	.18 – .284	1.50–2.15	62–82

[1] Data taken from Willis and Coleman (*11*). Their sources are given in the "data source" column.
[2] Graded sand.
[3] Constant.

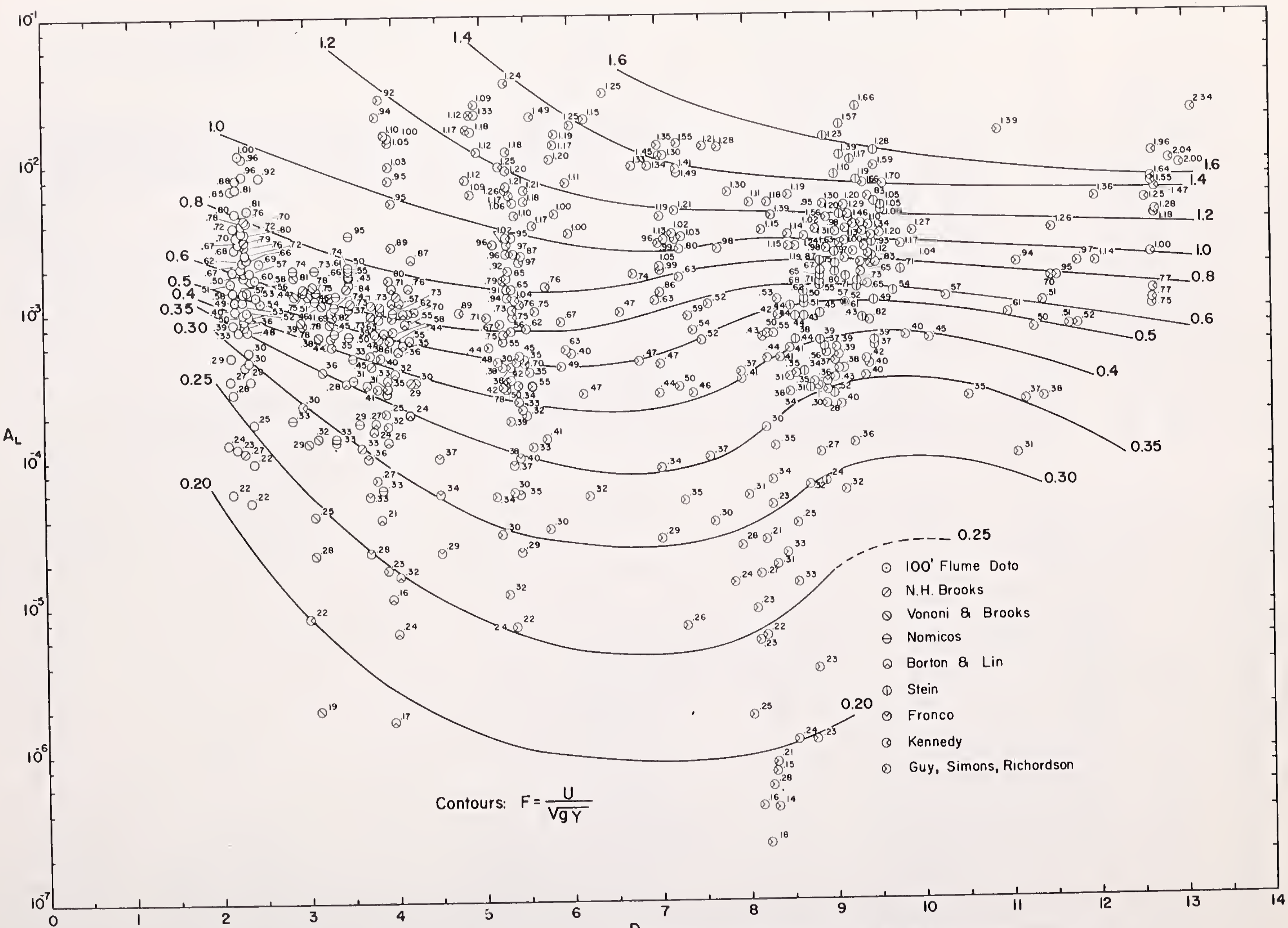

FIGURE 5.—Nondimensional sediment-discharge function based on flume data. (After Willis and Coleman, *11*.)

CALCULATIONS OF SEDIMENT-TRANSPORT CAPACITY

Based on the similitude principles discussed above, a computation method was developed that would predict the capacity sediment load that could be moved through a given channel section at various water discharges. The computation method requires the following preliminary information:

a. A water-discharge rating curve for the channel section. This may be based on observation, or it may be synthesized by some method.

b. Graphs of channel width, depth, and area plotted against either stage of discharge. These can be prepared with the water-discharge rating curve and a survey of the rated channel section.

c. A graph of $g^{1/3}/\nu^{1/3}$ plotted against water temperature. This can be prepared from the tabulations of ν for various temperatures, found in fluid mechanics textbooks like that of Rouse (*8*).

d. The median diameter of the bed material in the channel. This can be assumed, estimated, or determined for a particular site by standard sieve analysis of samples (*7*).

The computation procedure is simple enough to be performed with a slide rule or desk calculator. However, a computer program is convenient if a large number of predictions are to be made for a variety of bed materials and water temperatures. A suitable program is included in the appendix. The steps for the desk calculation procedure are as follows:

1. Tabulate the expected range of water discharges Q and the corresponding channel widths Z, depths Y and areas A. Use the curves prepared in accordance with steps a and b above.

2. Calculate the expected range of mean velocities U from $U=Q/A$.

3. Calculate the range of Froude numbers from equation 2.

4. With the graph of $g^{1/3}/\nu^{2/3}$ and the median bed-material diameter from steps c and d above, calculate D from equation 3 for each expected or assumed water temperature.

5. With D and F, the graph in figure 6 could be used to find A_L for each calculated value of F. However, A_L can be more conveniently found and tabulated in the calculation format by reading from table 2.

6. Calculate

$$\frac{\rho_s\rho_w}{\rho_s-\rho_w}gYU=\frac{5.14(1.94)}{(5.14-1.94)}gYU=3.12gYU,$$

where the values of ρ_s and ρ_w are in slugs per cubic foot and are essentially constant over a wide range of temperatures.

7. From equation 4, the capacity bed-material load in pounds per second per foot of channel width is $L=A_L(3.12gYU)$.

8. For the specified channel width at any discharge, the capacity sediment discharge G is $G=Lz$.

9. This can be converted from pounds per second to tons per day by dividing G by 0.023, if desired. Such a conversion would be usual in hydrologic calculations.

TESTING THE CALCULATION METHOD AGAINST FIELD DATA

In reducing the data from the field study, the sediment sample from each measurement of total sediment load was analyzed (*3*) by wet sieving to determine the amount of sand (particles larger than 0.062 mm) and the amount of fine sediment (particles smaller than 0.062 mm) being carried by the flow. Since the A_L values listed in table 2 were found from experiments with sands 0.1 mm in diameter and larger, it was not at first expected that the calculation method being tested could provide predictions of fine-sediment transport rates. The initial calculations were therefore confined to the determination of sand-transport rating curves for the normal channel section, at water temperatures of 35°, 50°, 60°, and 75° F, respectively. These rating curves are shown in figure 6, together with field measurements. The data show the typical scatter usually found in field sediment-transport measurements. Agreement between calculation and observation is poor or nonexistent.

According to the similitude theory used here, there is actually no such thing as a universal sand-transport rating curve for a given channel, but rather a family of curves for different D values and hence for different water temperatures. However, the stochastic nature of the field measurements and the discrepancies shown in the preceding figures suggested the calculation of an average sand-rating curve for the period of record of the field study. This was accomplished by using the average temperature of rec-

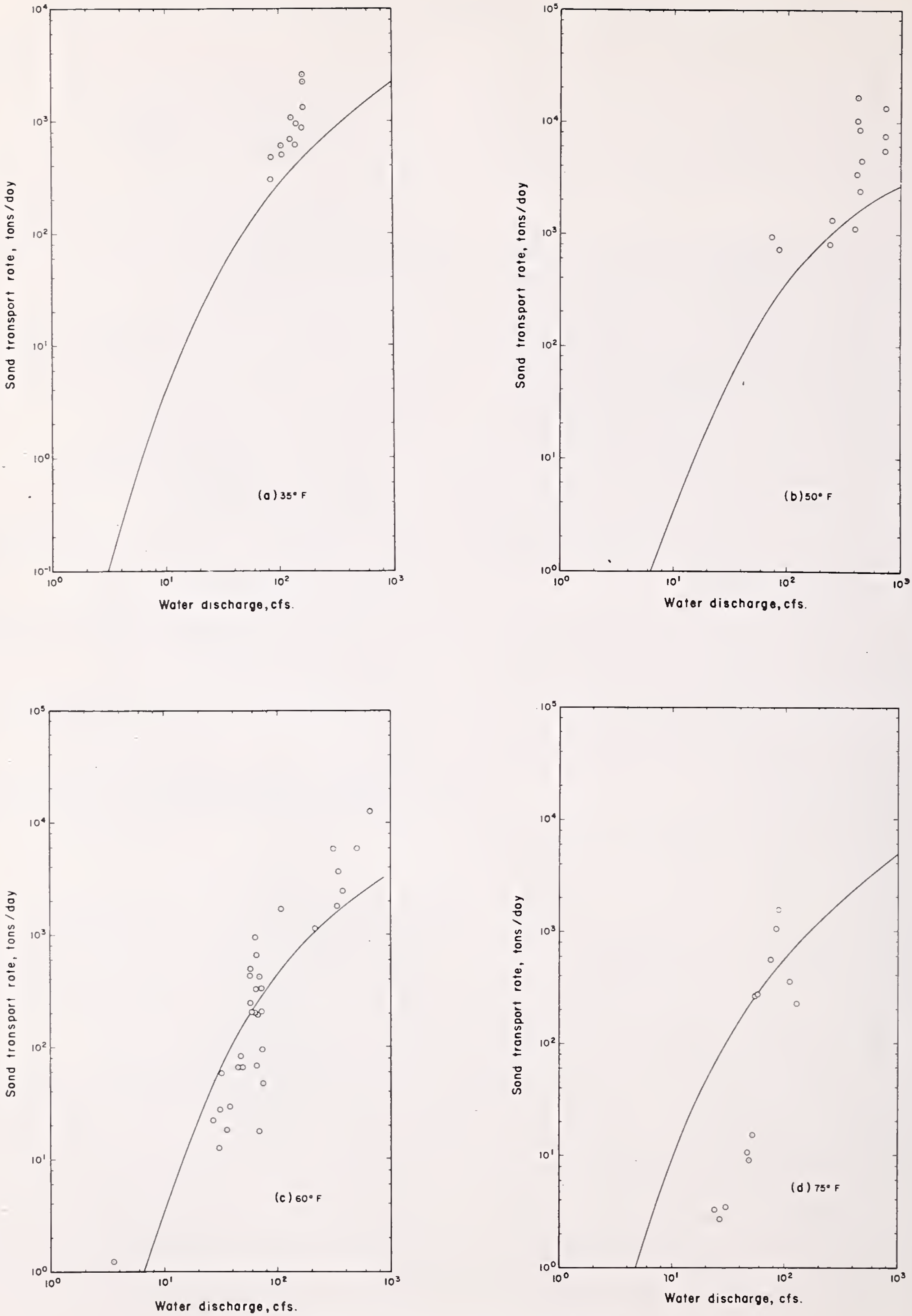

FIGURE 6.—Sand-transport rating curves.

TABLE 2.—*Values of A_L for values of F and D*

Value of *F*	Value of *D*: 2	3	4	5	6	7	8	9	10	11	12
0.2	5.0×10^{-4}	9.0×10^{-6}	2.7×10^{-6}	1.3×10^{-6}	9.2×10^{-7}	9.9×10^{-7}	9.2×10^{-7}	1.5×10^{-6}	....	....	....
.3	7.4×10^{-4}	2.4×10^{-4}	8.5×10^{-5}	3.8×10^{-5}	2.7×10^{-5}	2.4×10^{-5}	3.2×10^{-5}	8.5×10^{-5}	1.0×10^{-4}	7.6×10^{-5}	....
.4	1.2×10^{-3}	6.8×10^{-4}	4.2×10^{-4}	2.8×10^{-4}	2.2×10^{-4}	2.1×10^{-4}	3.6×10^{-4}	6.5×10^{-4}	6.7×10^{-4}	5.1×10^{-4}	3.2×10^{-4}
.5	1.5×10^{-3}	9.6×10^{-4}	6.4×10^{-5}	5.0×10^{-4}	4.4×10^{-4}	5.1×10^{-4}	8.9×10^{-4}	1.1×10^{-3}	1.1×10^{-3}	8.7×10^{-4}	6.6×10^{-4}
.6	2.1×10^{-3}	1.4×10^{-3}	9.2×10^{-5}	7.5×10^{-4}	6.5×10^{-4}	1.0×10^{-3}	1.4×10^{-3}	1.5×10^{-3}	1.4×10^{-3}	1.1×10^{-3}	9.4×10^{-4}
.7	3.2×10^{-3}	1.9×10^{-3}	1.3×10^{-3}	1.0×10^{-3}	9.8×10^{-4}	1.4×10^{-3}	1.7×10^{-3}	1.8×10^{-3}	1.7×10^{-3}	1.5×10^{-3}	1.2×10^{-3}
.8	5.2×10^{-3}	3.0×10^{-3}	2.0×10^{-3}	1.5×10^{-3}	1.4×10^{-3}	1.7×10^{-3}	2.1×10^{-3}	2.2×10^{-3}	2.1×10^{-3}	1.8×10^{-3}	1.6×10^{-3}
.9	9.0×10^{-3}	5.4×10^{-3}	3.3×10^{-3}	2.4×10^{-3}	2.0×10^{-3}	2.1×10^{-3}	2.5×10^{-3}	2.5×10^{-3}	2.4×10^{-3}	2.3×10^{-3}	2.0×10^{-3}
1.0	1.6×10^{-2}	1.0×10^{-2}	6.0×10^{-3}	4.0×10^{-3}	2.9×10^{-3}	2.6×10^{-3}	3.0×10^{-3}	3.0×10^{-3}	2.8×10^{-3}	2.6×10^{-3}	2.4×10^{-3}
1.1	....	....	1.3×10^{-2}	6.7×10^{-3}	4.2×10^{-3}	3.6×10^{-3}	3.7×10^{-3}	3.6×10^{-3}	3.5×10^{-3}	3.3×10^{-3}	3.0×10^{-3}
1.2	....	....	2.8×10^{-2}	1.2×10^{-2}	6.5×10^{-3}	5.0×10^{-3}	4.7×10^{-3}	4.5×10^{-3}	4.3×10^{-3}	4.0×10^{-3}	3.8×10^{-3}
1.3	....	....	....	....	....	7.3×10^{-3}	6.3×10^{-3}	5.7×10^{-3}	5.4×10^{-3}	5.0×10^{-3}	4.9×10^{-3}
1.4	....	....	....	....	....	1.1×10^{-2}	8.4×10^{-3}	7.4×10^{-3}	6.8×10^{-3}	6.5×10^{-3}	6.5×10^{-3}
1.5	....	....	....	....	....	1.8×10^{-2}	1.2×10^{-2}	1.0×10^{-2}	9.0×10^{-3}	8.8×10^{-3}	8.8×10^{-3}

ord (62.4° F) for calculating the boundary condition parameter *D*. The computation of the rating curve is given in table 3, and the curve, together with all field data, appears in figure 7. This graph indicates that the average calculated curve can be used for making reasonable estimates, on a statistical basis, of the capacity sand-transport rate for the channel involved. Agreement with individual observation is still no better than that achieved with other bed-material load formulas (*10*).

Although no experimentally determined values of *D* for particles less than 0.062 mm in diameter were available, the calculation method was applied to the prediction of transport rates for fine sediment, mainly in order to see what degree of error would result. In these computations, *D* values for a 0.1-mm particle size were used. Fine-sediment-transport rating curves are shown with field measurements in figures 8*a*–8*d* for water temperatures of 35°, 50°, 60°, and 75° F. The agreement between observation and cal-

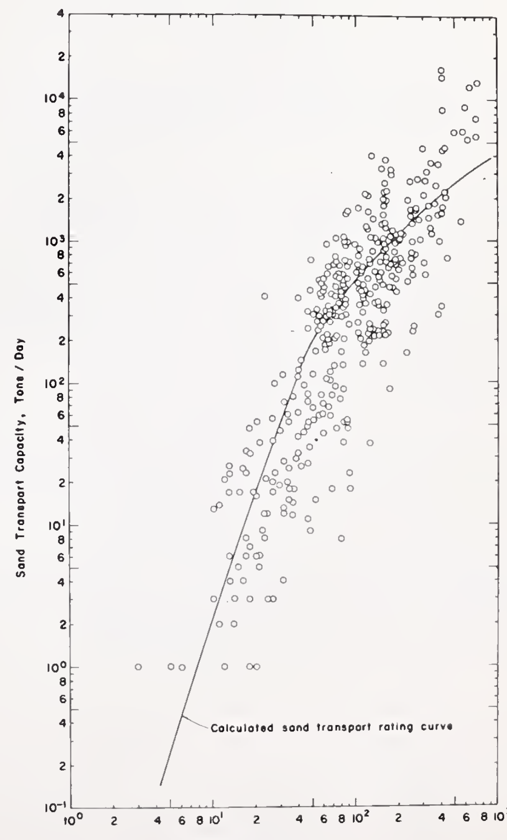

FIGURE 7.—Average sand-transport rating curve based on mean water temperature for the period of record.

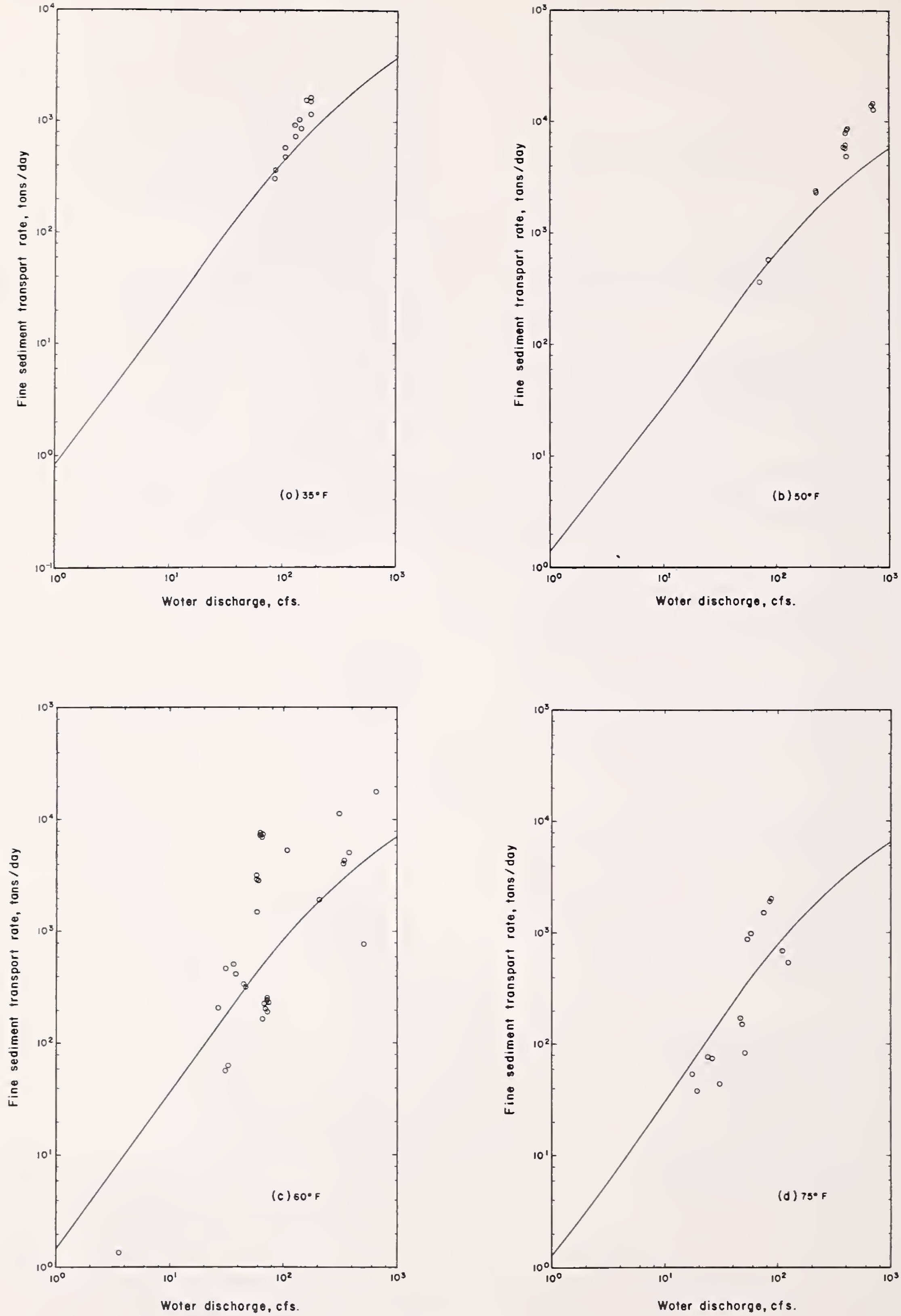

FIGURE 8.—Fine-sediment-transport rating curves.

culation is again poor, although generally better than for sand-transport rates. An average rating curve was also calculated for the fine sediment. The calculation is given in table 4, and the curve with field data is shown in figure 9. As in the transport of sand, this curve can evidently be used for making estimates of capacity fine-sediment transport rates for the channel.

CONCLUSIONS

The sediment-transport calculation method generates, for a given channel section and a given channel section and a given bed-material median diameter, a series of different sediment-transport rating curves for each water temperature. Comparison with field data from a particular channel section studied by Bowie et al. (*3*) showed that the calculated curves for given water temperatures were not in good agreement with measurement. However, the method could be used to provide average rating curves for estimating the transport rates of both sand-size material and fine sediment.

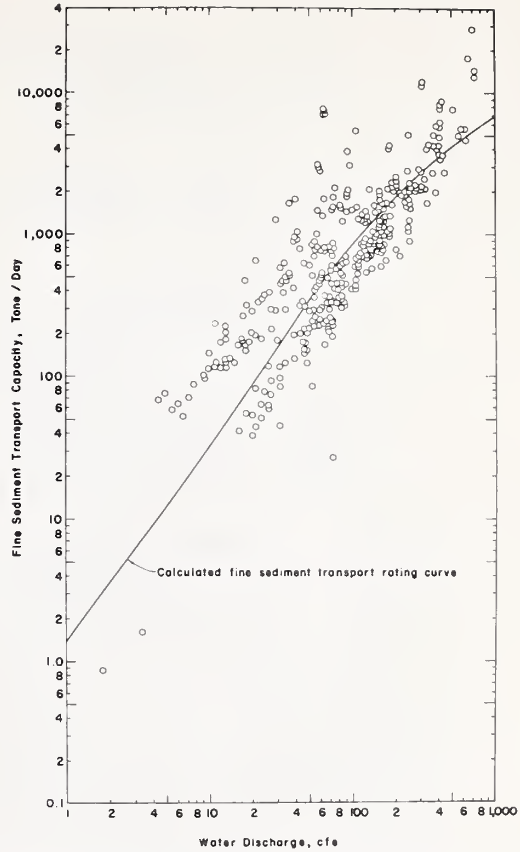

FIGURE 9.—Average fine-sediment-transport rating curve based on mean water temperature for the period of record.

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TABLE 3.—*Computation of the sand-transport rating curve*

Gage ht. (ft)	Q (ft^3/s)	z (ft)	Y (ft)	A (ft^2)	U (ft/s)	F	Temp. (° F)	d (mm)	D	A_L	$3.12gYU$ (lb/s/ft)	L (lb/s/ft)	G (lb/s)	G (tons/d)
1.77	5	25.85	0.25	6.46	0.77	0.27	62.4	0.38	7.68	1.1×10^{-5}	1.9×10^{1}	2.2×10^{-4}	5.6×10^{-3}	2.4×10^{-1}
1.85	10	26.35	.35	9.22	1.08	.32	....	....	....	5.0×10^{-5}	3.8×10^{1}	1.9×10^{-3}	5.0×10^{-2}	2.2
1.96	20	26.90	.49	13.18	1.52	.38	....	....	....	2.0×10^{-4}	7.4×10^{1}	1.5×10^{-2}	4.0×10^{-1}	1.7×10^{1}
2.16	50	27.68	.71	19.65	2.54	.53	....	....	....	9.4×10^{-4}	1.8×10^{2}	1.7×10^{-1}	4.7	2.0×10^{2}
2.42	100	28.54	1.03	29.40	3.40	.59	....	....	....	1.25×10^{-3}	3.5×10^{2}	4.4×10^{-1}	1.3×10^{1}	5.4×10^{2}
2.88	200	29.70	1.57	46.63	4.29	.60	....	....	....	1.30×10^{-3}	6.8×10^{2}	8.8×10^{-1}	2.6×10^{1}	1.1×10^{3}
3.95	500	31.70	2.85	90.34	5.53	.58	....	....	....	1.20×10^{-3}	1.6×10^{3}	1.9	6.0×10^{1}	2.6×10^{3}
5.43	1,000	33.75	4.61	155.60	6.42	.53	....	....	....	9.4×10^{-4}	3.0×10^{3}	2.8	9.4×10^{1}	4.1×10^{3}

TABLE 4.—*Computation of the fine-sediment rating curve*

Gage ht. (ft)	Q (ft^3/s)	z (ft)	Y (ft)	A (ft^2)	U (ft/s)	F	Temp. (° F)	d (mm)	D	A_L	$3.12gYU$ (lb/s/ft)	L (lb/s/ft)	G (lb/s)	G (tons/d)
1.77	5	25.85	0.25	6.46	0.77	0.27	62.4	0.10	2.08	4.6×10^{-4}	1.9×10^{1}	8.8×10^{-3}	2.2×10^{-1}	9.9
1.85	10	26.35	.35	9.22	1.08	.32	....	....	....	7.5×10^{-4}	3.8×10^{1}	2.8×10^{-2}	7.5×10^{-1}	3.3×10^{1}
1.96	20	26.90	.49	13.18	1.52	.38	....	....	....	9.8×10^{-4}	7.4×10^{1}	7.3×10^{-2}	1.9	8.6×10^{1}
2.16	50	27.68	.71	19.65	2.54	.53	....	....	....	1.6×10^{-3}	1.8×10^{2}	2.8×10^{-1}	7.9	3.4×10^{2}
2.42	100	28.54	1.03	29.40	3.40	.59	....	....	....	2.0×10^{-3}	3.5×10^{2}	6.9×10^{-1}	2.0×10^{1}	8.6×10^{2}
2.88	200	29.70	1.57	46.63	4.29	.60	....	....	....	2.1×10^{-3}	6.8×10^{2}	1.4	4.1×10^{1}	1.8×10^{3}
3.95	500	31.70	2.85	90.34	5.53	.58	....	....	....	1.9×10^{-3}	1.6×10^{3}	3.0	9.5×10^{1}	4.2×10^{3}
5.43	1,000	33.75	4.61	155.60	6.42	.53	....	....	....	1.6×10^{-3}	3.0×10^{3}	4.7	1.6×10^{2}	6.9×10^{3}

APPENDIX

```
      INTEGER TIME
      INTEGER TEMP
      REAL*8 DATE(10)
      REAL*4 NU,LOAD
      REAL*4 RT(200),VIS(90),SAC(200),ALG(15,12),WID(200)
      DIMENSION CO(10),C1(10),C2(10),C3(10)
      COMMON CO,C1,C2,C3
      COMMON RT,VIS,SAC,ALG,WID,STAGE,TEMP
C                    IDENTIFICATION OF VARIABLES
C     ****************************************************************************
C     ALG(J,K) - TABLE OF SEDIMENT TRANSPORT SIMILITUDE NUMBERS
C     AL       - SEDIMENT TRANSPORT SIMILITUDE NUMBER
C     A        - CROSS SECTIONAL AREA(SQ. FT.)
C     BIGD     - BOUNDARY CONDITION SIMILITUDE NUMBER
C     D50      - MEDIAN PARTICLE SIZE(FT)
C     DATE     - 80 CHARACTER IDENTIFICATION
C     F        - FROUDE NUMBER
C     G        - ACCERATION DUE TO GRAVITY
C     GHT      - WATER STAGE(FT)
C     LOAD     - SAND DISCHARGE(LBS/SEC/FT OF WIDTH)
C     Q        - WATER DISCHARGE(CFS)
C     QSP      - SAND DISCHARGE(LBS/SEC)
C     QST      - SAND DISCHARGE(TONS/DAY)
C     RT(J)    - WATER RATING TABLE(CFS)
C     SAC(J)   - CHANNEL DEPTH TABLE(FT)
C     U        - MEAN VELOCITY(FT/SEC)
C     VIS(J)   - KINEMATIC VISCOCITY
C     WID(J)   - CHANNEL WIDTH TABLE(FT)
C     Y        - FLOW DEPTH(FT)
C     Z        - CHANNEL WIDTH(FT)
C     TEMP     - WATER TEMPERATURE - F
C     SIZE     - GRAIN DIAMETER IN MILLIMETERS
C     ****************************************************************************
C     READ COEFFICIENTS FOR PARABOLIC INTERPOLATION
      DO 33322 JKL=1,15
      DO 33322 JKM=1,12
33322 ALG(JKL,JKM)=0.0
      READ(5,10) (CO(J),C1(J),C2(J),C3(J),J=1,10)
10    FORMAT(4F15.5)
      READ(5,11) J1,J2,J3,J4,K1
11    FORMAT(5I5)
C     READ WIDTH AND AREA TABLE
      READ(5,12) (WID(J),SAC(J),J=1,J1)
12    FORMAT(9X,F7.1,F10.2)
C     READ VISCOSITY TABLE
      READ(5,13) (VIS(J),J=1,J2)
13    FORMAT(4X,F7.3)
```

```
C      READ WATER RATING TABLE
       READ(5,14) (RT(J),J=1,J3)
14     FORMAT(12X,F12.4)
C      READ SEDIMENT TRANSPORT SIMILITUDE TABLE
       READ(5,15) ((ALG(J,K),K=2,K1),J=2,J4)
15     FORMAT(8F10.8/3F10.8)
C      READ DATE AND/OR OTHER IDENTIFICATION
161    READ(5,17)DATE
17     FORMAT(10A8)
       READ(5,1) SIZE
1      FORMAT(F5.2)
       D50 = SIZE/304.8
       G = 32.174
       N = 0
       LOAD = 0.0
       QSP = 0.0
       Z = 0.0
       Y = 0.0
       Q = 0.0
       U = 0.0
       AL= 0.0
       WRITE(6,16) SIZE,DATE
16     FORMAT('1',T30,'SAND DISCHARGE BY SIMILITUDE METHOD'/' '10A8  /
      1' '10A8 /
      1' TIME  GHT TEMP      Q      Z     Y      A    U     F     AL        BKJ
      2      QSP          QST              OBS')
20     READ(5,21,END=50) TIME,STAGE,TEMP
21     FORMAT(T13,I4,F5.2,T66,I2,T22,F6.0,1X,F7.0,T44,F6.0)
       IF(TEMP.LT.74.OR.TEMP.GT.75) GO TO 20
       IF(STAGE.LE.0.0) GO TO 20
       IF(TEMP.LE.0) GO TO 20
       IF(TIME.EQ.9) GO TO 161
       CALL ZY(Z,Y,N)
       A = Z*Y
       CALL QW(A,Q,U,N)
       F = U/SQRT(G*Y)
       FUOF = (G*Y*U)/0.321
       NU = VIS(TEMP-31)*0.00001
       BIGD = (G**(1./3.)/NU**(2./3.))*D50
       CALL GRAPH(BIGD,F,AL)
       LOAD = AL*(G*Y*U/0.321)
       QSP = LOAD*Z
       QST = QSP*43.2
       AL = AL*1000.
       IF(F.LE.0.0.OR.BIGD.LE.0.0) GO TO 96325
       IF(F*10.GT.12.OR.BIGD.GT.15.) GO TO 96325
       WRITE(6,51) TIME,STAGE,TEMP,Q,Z,Y,A,U,F,AL,LOAD,QSP,QST
51     FORMAT(' 'I4,F6.2,I4,F8.2,2F5.1,F6.1,2F5.2,F7.4,F9.2,F10.2,2F12.2,
85214 FORMAT(2F10.2)
96325  CONTINUE
       GO TO 20
50     CONTINUE
       CALL EXIT
       END
```

```
      SUBROUTINE ZY(Z,Y,N)
      REAL*4 RT(200),VIS(90),SAC(200),ALG(15,12),WID(200)
      DIMENSION C0(10),C1(10),C2(10),C3(10)
      COMMON C0,C1,C2,C3
      COMMON RT,VIS,SAC,ALG,WID,STAGE,TEMP
      DF = STAGE*10.0+1.0005-16.0
      N = DF
      DF = DF-N
      Z = WID(N)+(WID(N+1)-WID(N))*DF
      Y = SAC(N)+(SAC(N+1)-SAC(N))*DF
      RETURN
      END
      SUBROUTINE QW(A,Q,U,N)
      REAL*4 RT(200),VIS(90),SAC(200),ALG(15,12),WID(200)
      DIMENSION C0(10),C1(10),C2(10),C3(10)
      COMMON C0,C1,C2,C3
      COMMON RT,VIS,SAC,ALG,WID,STAGE,TEMP
C     A = AREA   WIDTH * DEPTH
C     Q = WATER IN CFS FROM TABLE
C     U = MEAN VEL. COMPUTED ---Q/A
      N = N+16
      K = STAGE*100.0+0.5
      K = K-K/10*10+1
      Q = C0(K)*RT(N-1)+C1(K)*RT(N)+C2(K)*RT(N+1)+C3(K)*RT(N+2)
      U = Q/A
      RETURN
      END
      SUBROUTINE GRAPH(BIGD,F,AL)
      REAL*4 RT(200),VIS(90),SAC(200),ALG(15,12),WID(200)
      DIMENSION C0(10),C1(10),C2(10),C3(10)
      COMMON C0,C1,C2,C3
      COMMON RT,VIS,SAC,ALG,WID,STAGE,TEMP
C     FIND UPPER LEFT CORNER OF BOUNDRY (K & L)
      K = BIGD
      L = F*10.
      D = BIGD
      A = ALG(L,K)+(D-K)*(ALG(L,K+1)-ALG(L,K))
      B = ALG(L+1,K)+(D-K)*(ALG(L+1,K+1)-ALG(L+1,K))
      AL = A+(F*10.0-L)*(B-A)
      RETURN
      END
```

SEDIMENT-YIELD PREDICTION WITH UNIVERSAL EQUATION USING RUNOFF ENERGY FACTOR[1]

By Jimmy R. Williams[2]

INTRODUCTION

The universal soil loss equation (*16*)[3] was developed for predicting field soil loss as a guide to conservation farm planning, but it can be used to predict sediment yield from watersheds when a delivery ratio is applied (*1, 10, 13*). Delivery ratios (the sediment yield at any point along a channel divided by the source erosion above that point) have been computed for some physiographic areas (*5, 7–9*) and related to watershed characteristics. However, the few areas studied represent only a small portion of the United States.

The delivery ratio is not necessary if the rainfall energy factor of the universal equation is replaced by a runoff rate factor. Watershed characteristics such as drainage area, stream slope, and watershed shape influence runoff rates and delivery ratios in a similar manner. For example, a high stream slope produces high runoff rates and high delivery ratios.

Besides eliminating the need for a delivery ratio, the runoff factor increases the accuracy of the universal equation. Although runoff is highly correlated with rainfall energy, it is also affected considerably by antecedent soil moisture. If the soil moisture is low, large-energy rainstorms may produce little or no runoff. Without runoff there can be no sediment yield.

The universal equation was developed for predicting annual sediment yield. The modified equation presented here was developed to predict sediment yield for individual storms. A method of predicting sediment yield based on individual storms should be more accurate than annual prediction procedures.

In a previous study (*15*) a runoff factor proved superior to rainfall for predicting sediment concentrations from five small watersheds in the Texas Blacklands. Dragoun and Miller (*4*) found that a runoff factor was the best single predictor of sediment yield for two small watersheds in Nebraska. The Committee on Sedimentation of the Hydraulics Division, American Society of Civil Engineers (*12*), stated that runoff is the best single indicator of sediment yield. The committee also pointed out that the use of runoff rate for determining sediment yield is feasible, because numerous short-term runoff records for watersheds throughout the country can be extended by applying an assumed rainfall-runoff relationship to long-term rainfall records. More accurate results may be obtained by using one of several available runoff prediction models such as the Stanford model (*2*), USDAHL-70 model (*6*), HYMO (*14*), or the Soil Conservation Service model (*12*). The choice of runoff model depends upon available inputs, time requirements, and desired accuracy.

The runoff prediction models can be used to compute hydrographs for watersheds. Therefore, the runoff rate and volume are available to form a prediction factor. The runoff rates and volumes were substituted for the rainfall energy factor in the universal equation, and an optimization technique (*3*) was used to determine the prediction equation.

[1] Cooperative research of the Agricultural Research Service, U.S. Department of Agriculture, and the Texas Agricultural Experiment Station, Texas A&M University.

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[3] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this paper.

MODIFIED UNIVERSAL SOIL LOSS EQUATION

The universal equation is

$$A = R \times K \times LS \times C \times P \qquad (1)$$

where A=the computed soil loss in tons per acre,
R=the rainfall factor,
K=the soil-erodibility factor,
LS=the slope length and gradient factor,
C=the cropping management factor,
and P=the erosion-control-practice factor.

In previous work (*13*) the universal equation was modified for watershed application. The K, LS, C, and P factors were weighted according to drainage area so that the source erosion can be computed for the entire watershed in one solution of the equation. The general form of the weighting function is

$$X = \frac{\sum_{i=1}^{n} X_i DA_i}{DA} \qquad (2)$$

where X=weighted factor,
X_i=value of the factor covering drainage area DA_i,
and DA=total drainage area of the watershed.

Only the cultivated area of a watershed is considered in computing the P factor. The three erosion-control practices and their values are as follows:

Practice	P
Straight rows	1.0
Straight rows with grassed waterways	.3
Terraces with grassed waterways	.1

The remaining two factors, A and R, must be considered when the runoff factor is installed. Since previous work has shown that runoff is more highly correlated to sediment loss than is rainfall, the rainfall factor, R, in equation 1 is replaced by a runoff factor. Three forms of the runoff factor were investigated for each of two forms of equation 1. These were as follows:

A	R
tpa	$B_1(in+iph)^{B_2}$
tpa	$B_1(in \times iph)^{B_2}$
tpa	$B_1 \times in^{B_2} \times iph^{B_3}$
t	$B_1(af+cfs)^{B_2}$
t	$B_1(af \times cfs)^{B_2}$
t	$B_1 \times af^{B_2} \times cfs^{B_3}$

where tpa=sediment yield in tons per acre,
B_1=constants determined by optimization,
in=volume of runoff in inches,
iph=peak runoff rate in inches per hour,
t=sediment yield in tons,
af=volume of runoff in acre-feet,
and cfs=peak runoff rate in cubic feet per second.

Besides using the peak runoff rates, a weighted runoff rate was determined for each storm and substituted for the peak rates. The weighting equation is

$$q_w = \frac{\sum_{i=1}^{n} Q_i \times q_i}{Q}, \qquad (3)$$

where q_w=weighted runoff rate,
Q_i=incremental runoff volume,
q_i=incremental runoff rate,
and Q=total runoff volume.

DATA DESCRIPTION

The data used to evaluate the various forms of the modified universal equation were collected from 18 small watersheds. The collection periods and the watershed areas ranged considerably. During 1939–43, data were collected from eleven 3-acre watersheds near Riesel, Tex. Data were also collected at Riesel during 1960–70 from five watersheds with areas ranging from 132 to 4,380 acres. At Hastings, Nebr., data were collected during 1957–66 from two watersheds with areas of about 450 acres. These data contained a total of 778 individual storms. Table 1 describes the data for each watershed.

The soils at Riesel are Blackland Prairie soils that have a high content of montmorillonite clay. The Hastings soils have a silt loam texture and

TABLE 1.—*Description of watershed data*

Watershed	Location	Drainage area (acres)	Average land slope (pct)	Slope length (ft)	Number of events
SW-2	Riesel, Tex.	2.70	1.91	400	26
SW-3	do	3.09	1.91	450	20
SW-5	do	3.09	3.27	450	32
SW-6	do	3.04	3.18	410	28
SW-7	do	3.15	1.67	470	32
SW-11	do	3.23	.94	400	27
SW-12	do	2.97	3.81	380	16
SW-13	do	3.19	3.07	430	33
SW-16	do	3.17	2.58	440	39
SW-17	do	2.99	1.83	380	32
SW-18	do	3.04	1.14	460	33
Y-2	do	132	2.57	240	55
W-1	do	176	2.19	274	59
Y	do	309	2.41	393	58
D	do	1,110	2.10	298	69
G	do	4,380	2.06	346	68
W-3	Hastings, Nebr.	481	5.40	218	97
W-5	do	411	5.90	258	54
Total					778

are representative of the loessial soils region. Average annual rainfall is about 34 inches at Riesel and 24 inches at Hastings. Land use ranged considerably for the 18 watersheds. Ten of the eleven 3-acre watersheds were cultivated, and one was native meadow. Land use on the larger watersheds ranged from high percentages of cultivated land on Y-2, Y, W-1, W-3, and W-5 to high percentages of pasture and other nontilled land on watersheds D and G.

The two erosion control practices used for the cultivated areas of the watersheds were terraces and grassed waterways. Ten of the 3-acre watersheds were cultivated with straight rows and without terraces or waterways. Watersheds Y and Y-2 were conservation watersheds. All cultivated lands with slopes greater than 1 pct were terraced and had grassed waterways. All tillage operations were parallel to the terraces. Watershed W-1 had no terraces but did have grassed waterways to carry the outflow from cultivated areas to the main-stem channel. The watershed was cultivated in straight rows parallel to field boundaries without regard to slope. Watersheds D and G had some cultivated land that was terraced and some that was not. Most of the cultivated areas, especially the terraced areas, had waterways. However, some of these terraces and waterways were not as well maintained as those on watersheds Y, Y-2, and W-1. Watershed W-3 was farmed with straight rows. Watershed W-5 was predominantly farmed in accordance with the best recommended conservation measures.

DEVELOPMENT OF EQUATION

To determine the most accurate prediction equation, each form of the runoff and sediment-yield factors discussed earlier was substituted into the universal equation and evaluated by optimization (*3*). The equation that best fit the data was

$$S=95(Q\times q_p)^{0.56}\times K\times LS\times C\times P. \qquad (4)$$

where S=sediment yield in tons,
Q=volume of runoff in acre-feet,
and q_p=peak flow rate in cubic feet per second.

Equation 4 explains about 92 pct of the variation in sediment yield. Another form of the runoff factor, $B_1\times af^{B_2}\times cfs^{B_3}$, can be substituted into equation 4 with no loss of prediction accuracy. Since both forms predicted equally, the simpler form was chosen.

DISCUSSION OF RESULTS

Besides explaining a large percentage of the total variation in sediment yield, it is also important to have uniform prediction accuracy for each watershed. As an example, some forms of the prediction equation explained almost as much of the total variation as equation 4, but predicted too high for some watersheds and too low for others. Equation 4 is also more accurate for large storms than for small ones. Since a few large storms produce most of the sediment yield, it is important to be more accurate in predicting the big-storm sediment yields. This feature is forced on equation 4 by the optimization procedure because the coefficients are adjusted to minimize the error. Since the magnitude of the error is much greater for large storms, the large storms influence the coefficients of the equation more. For this reason, some forms of the equation overpredicted sediment yields from the small watersheds. To demonstrate the performance of equation 4, figures 1–5 show the observed

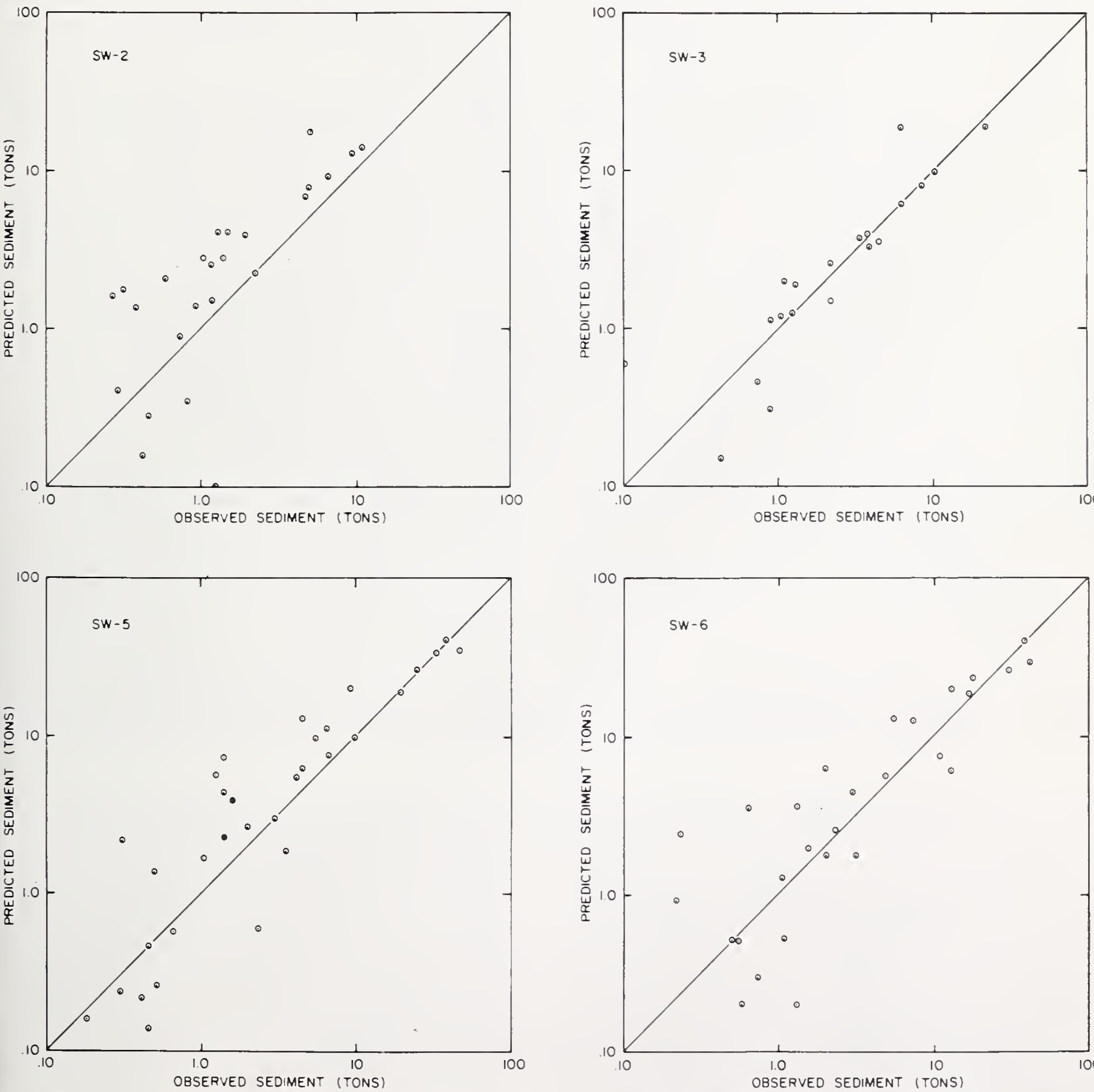

FIGURE 1.—Comparison of observed and predicted sediment yields for watersheds SW-2, SW-3, SW-5, and SW-6.

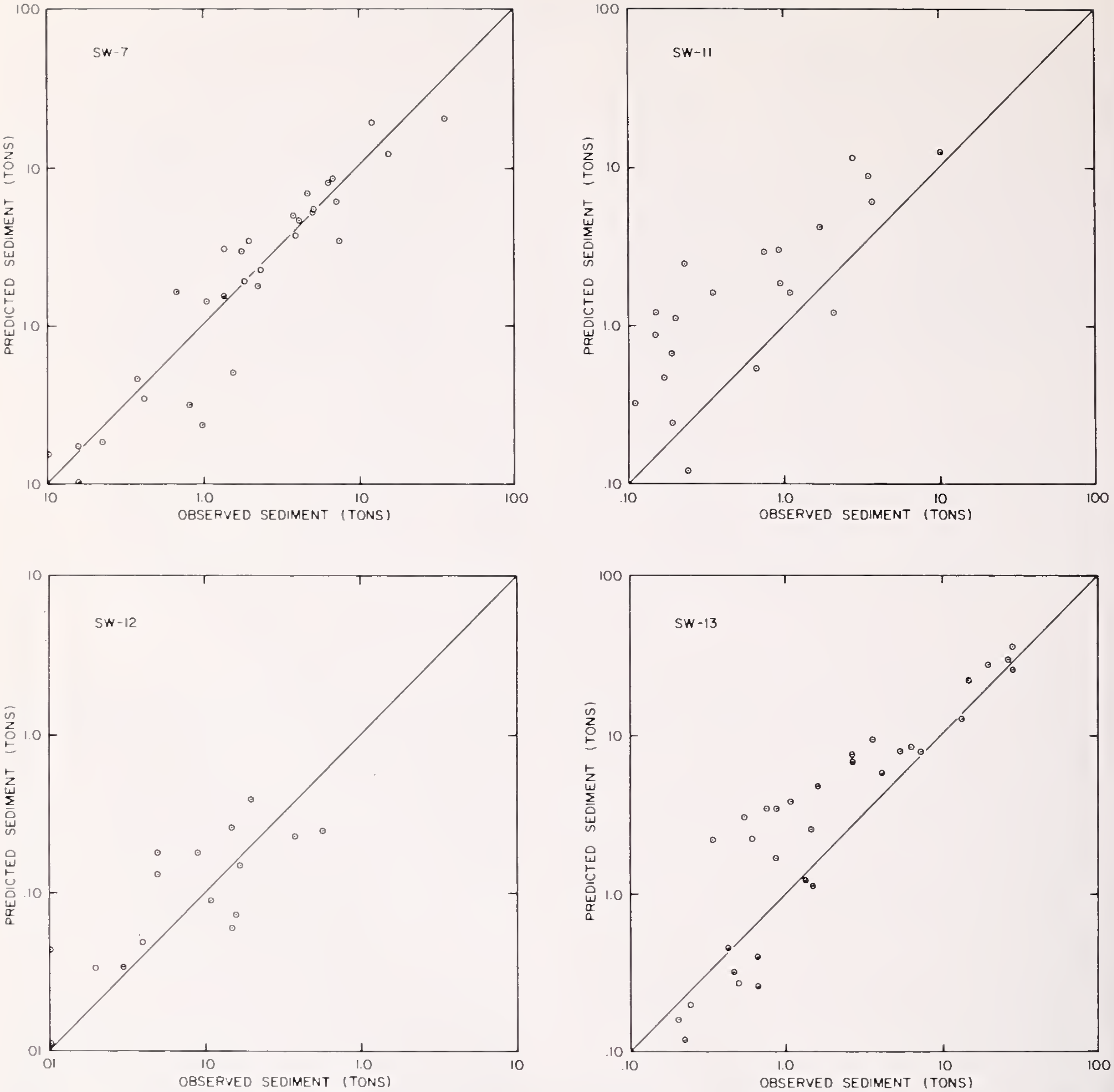

FIGURE 2.—Comparison of observed and predicted sediment yields for watersheds SW-7, SW-11, SW-12, and SW-13.

versus the predicted sediment yields for each watershed.

The eleven 3-acre watersheds were used to compare the accuracy of equation 4 with that of the universal soil loss equation, with rainfall on a storm basis. These small watersheds are ideal for the comparison because the delivery ratio and the erosion-control-practice factor are 1.0 for each watershed. The values of K, C, and LS were the same for both equations. Therefore, the only difference was between the rainfall and runoff factors. Equation 4 explained 82 pct and the universal equation explained 47 pct of the variation in sediment yield for the small watersheds.

The universal equation and equation 4 were also compared for the five largest watersheds at Riesel. The annual sediment production was computed previously (*13*) with the universal equation to determine delivery ratios. The delivery ratio was computed by dividing the measured sediment yield for an 8-yr period by the sum of the annual predicted sediment production. To de-

termine the annual sediment yields with the universal equation, the computed delivery ratio for each watershed was multiplied by the predicted sediment production for each year. The annual sediment yields were computed with equation 4 by summing predicted yields for individual storms in each year. The average annual percentage errors for each watershed are shown in the following table.

The universal equation overpredicted sediment production for years with low rainfall factors and underpredicted sediment production for years with high rainfall factors.

Watershed	Percent error	
	Universal equation	Equation 4
G	43	15
D	66	37
W-1	62	15
Y	59	13
Y-2	73	24

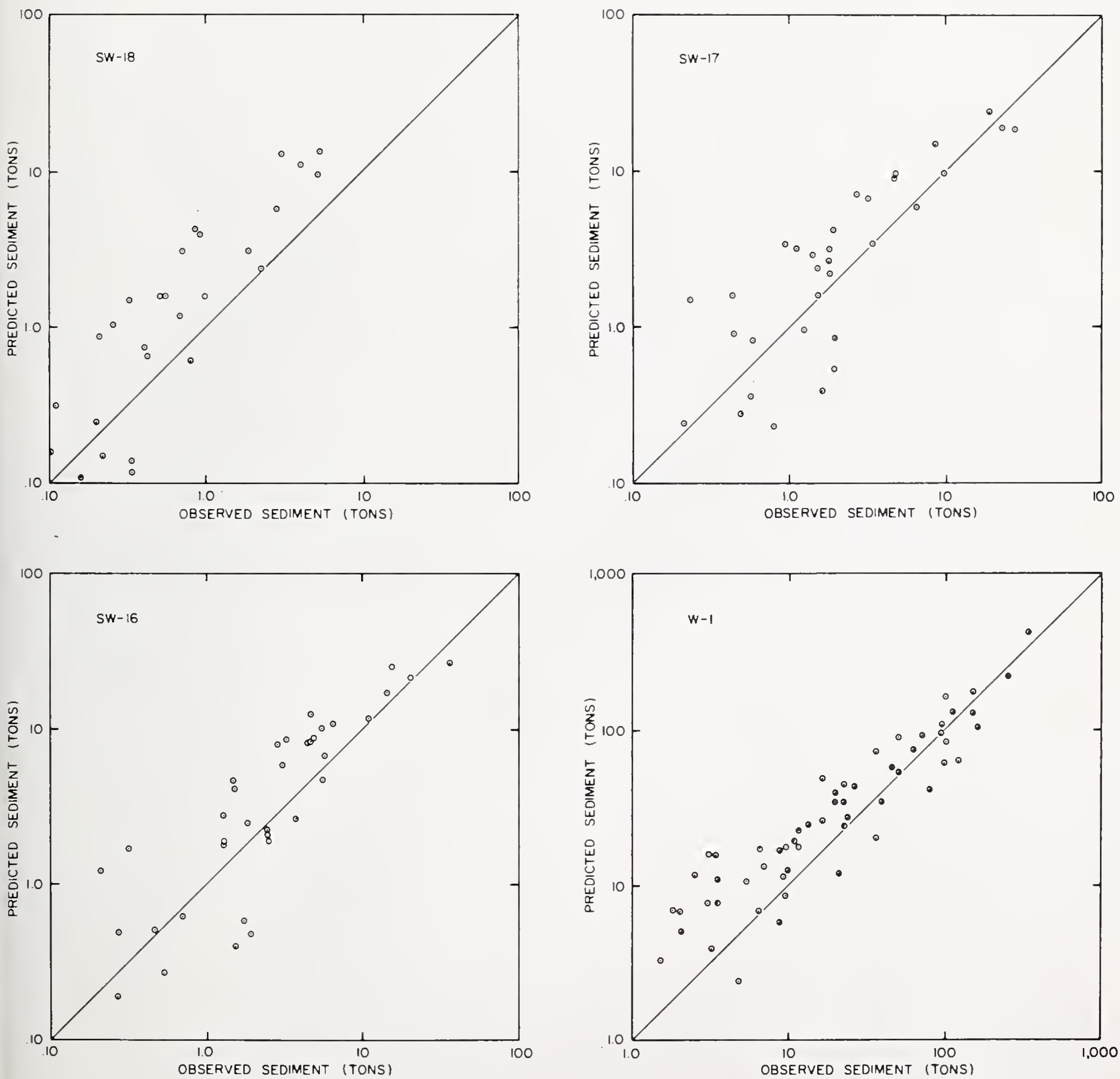

FIGURE 3.—Comparison of observed and predicted sediment yields for watersheds SW-18, SW-17, SW-16, and W-1.

Besides determining and evaluating a runoff factor for the universal equation, the erosion-control-practice factor was studied. The other factors of the equation, K, LS, and C, have been determined for plots (*17*) and can be applied to watersheds. However, guidelines for determining the P factor for watersheds are not completely developed. The P factors were estimated for this study according to the guidelines suggested in a previous study (*13*). The determination of P factors was quite simple for several of the watersheds. Since erosion control was not practiced on any of the 3-acre watersheds, their P factor was 1.0. Watersheds Y and Y-2 were conservation watersheds, so their P factors were estimated to be 0.1. The other watersheds fell between these extremes. It was difficult to estimate P factors for the Hastings watersheds because information about erosion control was incomplete. A prediction equation similar to equa-

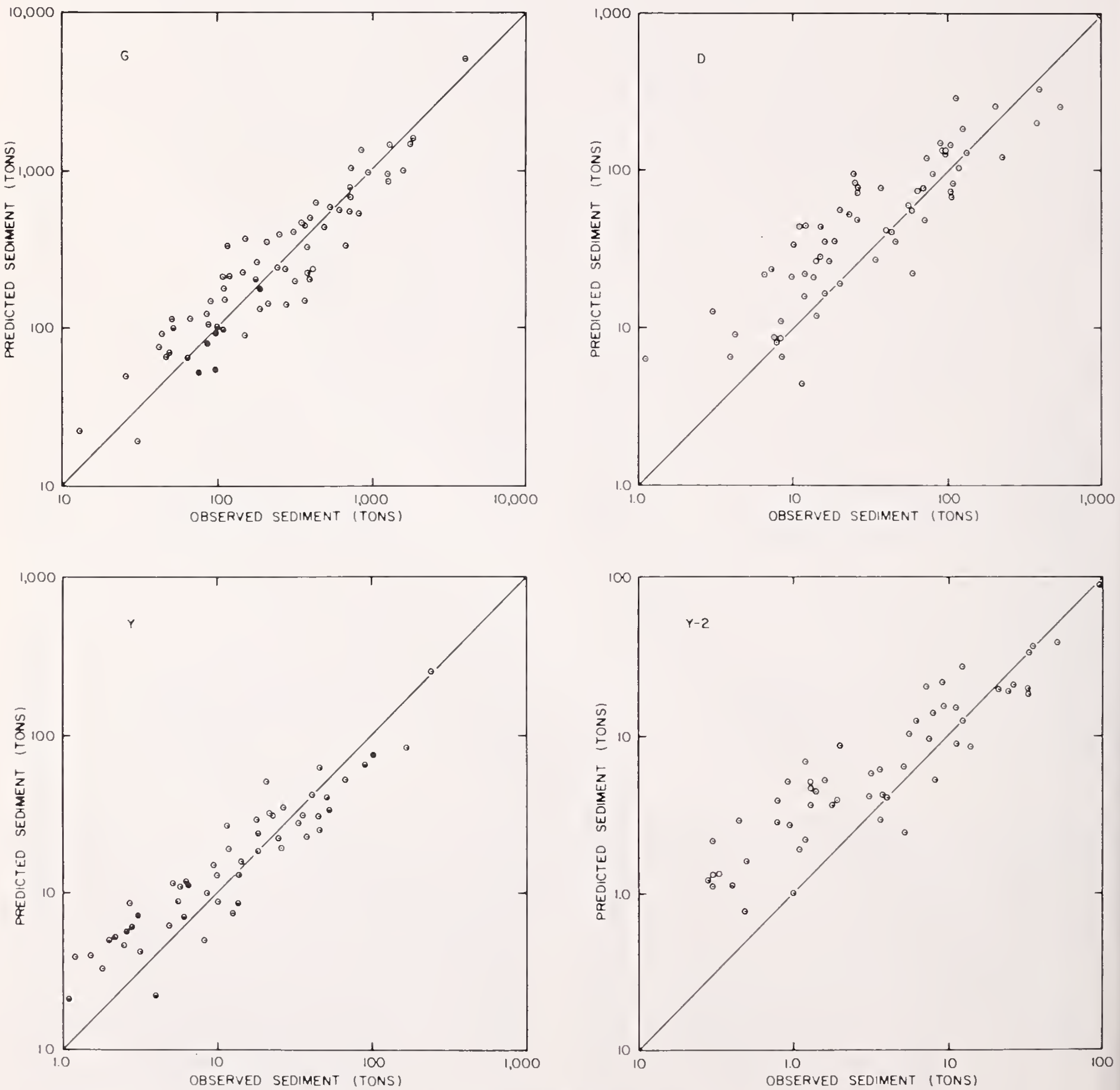

FIGURE 4.—Comparison of observed and predicted sediment yields for watersheds G, D, Y, and Y-2.

tion 4 was developed with the initial estimates of the P factors. The P factors were then adjusted to make the sum of the errors equal zero for each watershed. The adjusted P factors for each watershed are shown in the following table.

The adjustments were restricted so that the P factors for the 3-acre watersheds had to be 1.0. This forced a slight increase in most of the other estimated P factors. The adjusted P factors for watersheds Y and Y-2 indicate that P should be 0.2 for watersheds that are terraced and have waterways. Since the only conservation practice used on watershed W-1 was grassed waterways, the grassed-waterway P factor is changed from 0.3 to 0.4.

Watershed	P	Watershed	P
G	0.40	SW-7	1.00
D	.30	SW-11	1.00
W-1	.40	SW-12	1.00
Y	.20	SW-13	1.00
Y-2	.20	SW-16	1.00
SW-2	1.00	SW-17	1.00
SW-3	1.00	SW-18	1.00
SW-5	1.00	W-3	.45
SW-6	1.00	W-5	.40

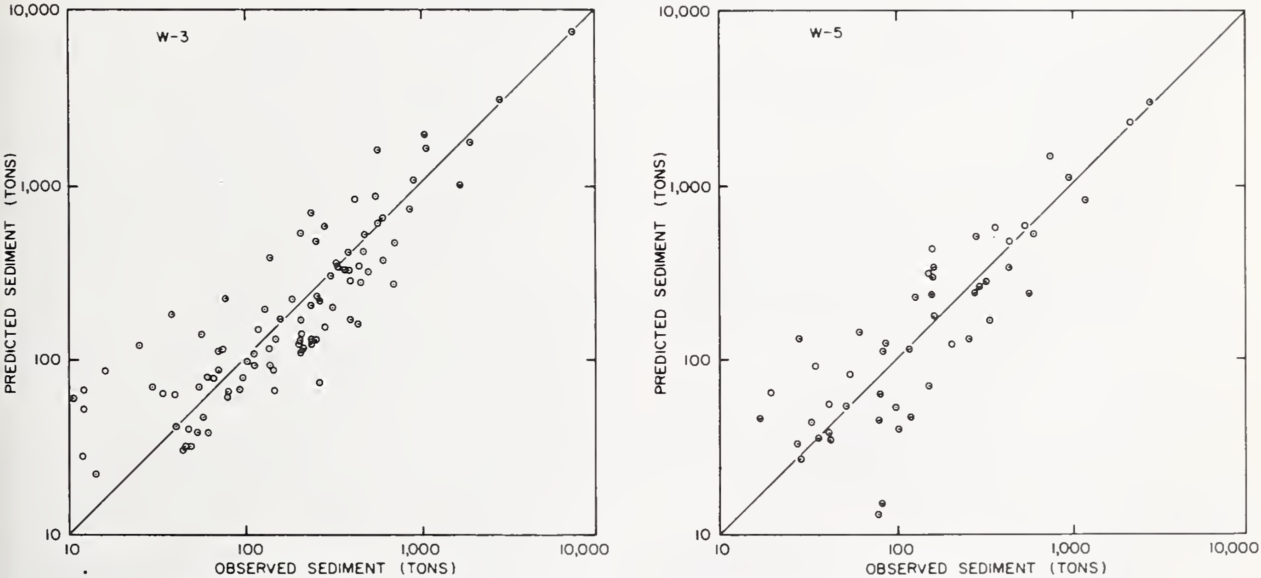

FIGURE 5.—Comparison of observed and predicted sediment yields for watersheds W-3 and W-5.

SUMMARY AND CONCLUSIONS

The rainfall energy factor of the universal soil loss equation was replaced by a runoff factor (volume of runoff $\times$ peak runoff rate for a storm). The modified equation eliminates the need for a delivery ratio and is more accurate than the original equation. Data from 18 small watersheds were used to develop the modified equation which explained about 92 pct of the variation in sediment yield.

The erosion-control-practice factor was adjusted for watershed application. P was determined to be 0.2 for terraces and waterways and 0.4 for waterways only.

Although the runoff factor is a good sediment-yield predictor, more research is needed to insure that the modified equation is applicable to most small watersheds. All available small-watershed sediment data should be analyzed to determine the optimum values of the coefficients in the prediction equation. Also, more work is needed to determine guidelines for selecting erosion-control-practice factors for watersheds.

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SEDIMENT YIELD AS RELATED TO A STOCHASTIC MODEL OF EPHEMERAL RUNOFF

By K. G. Renard and L. J. Lane[1]

Ephemeral streams in areas subject to air-mass thunderstorms characteristically have highly variable runoff. Quantification of such runoff is difficult but necessary before the sediment yield of a watershed can be estimated.

Provisions for sedimentation processes should be an integral part of design, construction, or maintenance of conservation measures in a watershed. Although progress has been made toward understanding the processes of sedimentation, such as the detachment, entrainment, transport, deposition, and consolidation of fluvial sediments, much work remains. We believe that significant progress toward predicting sediment yield can be made by coupling hydrologic models (or phases of the hydrologic cycle) to analytical models of sedimentation processes.

Sedimentation and hydrologic processes have essential similarities in humid and arid areas, but there are major differences involved in their boundary conditions. Figure 1 shows that conceptually, even with tributary inflow, the discharge of an ephemeral stream may remain the same or decrease downstream because of the continual water loss to the coarse streambed. Such losses in ephemeral streams may dominate the streamflow response to precipitation events. Although transmission losses in ephemeral channels has been discussed extensively (*1, 2, 5, 6, 11, 12, 14, 15, 19, 20, 21, 24*),[2] satisfactory analytic models for use on ungaged basins within a region are not yet available.

As an alternative to determining the runoff at a specific point and then routing it in time and space, certain runoff properties can be quantified by modeling the runoff as a stochastic process. Data on storm occurrences in time and space and magnitudes of the individual events are necessary for a model relating runoff and sediment yield. A stochastic model that preserves the special conditions encountered in ephemeral streams in semiarid regions can be developed.

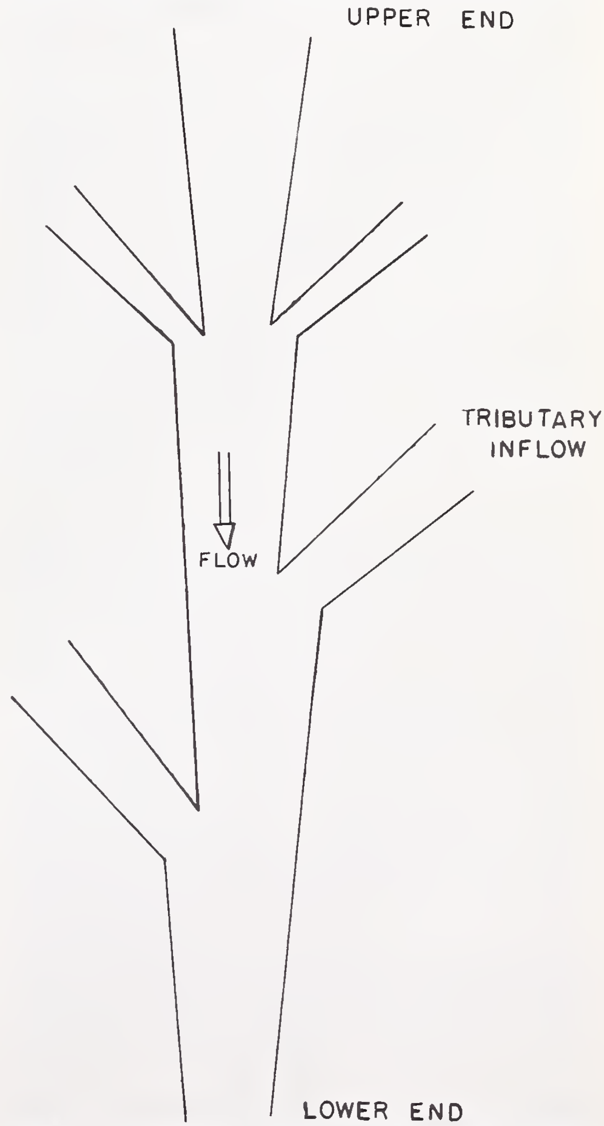

FIGURE 1.—Conceptual model of an ephemeral stream reach with discharge porportional to stream width.

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[2] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this paper.

DESCRIPTION OF WATERSHED

The sediment-yield model described in this paper incorporates a stochastic model of runoff with a deterministic sediment-transport relation. It was developed and verified with field data for the Walnut Gulch Experimental Watershed near Tombstone in southeastern Arizona (fig. 2). The watershed, which is operated by the Agricultural Research Service, contains 95 recording rain gages and 11 major, critical-depth, streamflow measuring stations. The 58-mi^2 watershed has an average annual precipitation of 14 inches and is representative of much of the mixed grass-bush rangeland in southeastern Arizona and southwestern New Mexico. Most of the watershed is grazed year around. Elevations in the watershed range from 4,000 ft above mean sea level at the watershed outlet to over 6,000 ft. Most of the watershed consists of gently rolling, low hills typical of the intermountain Basin and Range province, with only about 1 mi^2 of the watershed in the headwaters of the Little Dragoon Mountains.

STOCHASTIC MODEL OF RUNOFF

Techniques have been developed for using stochastic models in water-resource systems (*10*). Maass et al. (*18*) suggested the use of synthetic data to partially overcome the problem of short-duration data. Benson and Matalas (*3*) used statistical parameters estimated from the physical and climatic characteristics of drainage basins to generate data at ungaged locations. More relevant to analysis of runoff on semiarid areas such as Walnut Gulch is the work of Kisiel, Duckstein, and Fogel (*13*) concerning the analysis and modeling of ephemeral streamflow. Further analysis (*9*) related rainfall and runoff for summer storms. In their analysis, a Poisson distribution was used to model the number of events per season. The assumption of a Poisson distribution was based on the work of Brooks and Carruthers (*4*) and Todorovic and Yevjevich (*22*). Duckstein, Fogel, and Kisiel (*9*) modeled the rainfall depth at a point as a geometric random variable and the areal rainfall as a negative binomial random variable. The runoff volumes were obtained by assuming a linear rainfall-runoff relationship and then randomizing the coefficient.

As an alternative to a rainfall-runoff model, a stochastic model of ephemeral runoff was developed with data from the Walnut Gulch Experimental Watershed (*7, 8, 16*). This stochastic model, which is summarized in figure 3 and table 1, generates intermittent and independent runoff events and was used as a starting point for the study reported here. Two variables were used to describe the runoff season: (1) the starting date of the summer runoff season and (2) the number of runoff events recorded at the watershed outlet per season. The temporal distribution of the runoff events was described by two variables: (1) the event time of day and (2) the interval between events. Each runoff event was described by two random variables: (1) runoff volume and (2) peak discharge. Runoff volume and peak discharge were highly correlated so that the peak discharge could be generated from the runoff volume. The synthetic data generation process is shown in figure 3. A final characterization of the model is given by the assumed distributions for the random variables. These assumed distributions, modified from Diskin and Lane (*8*), are given in table 1.

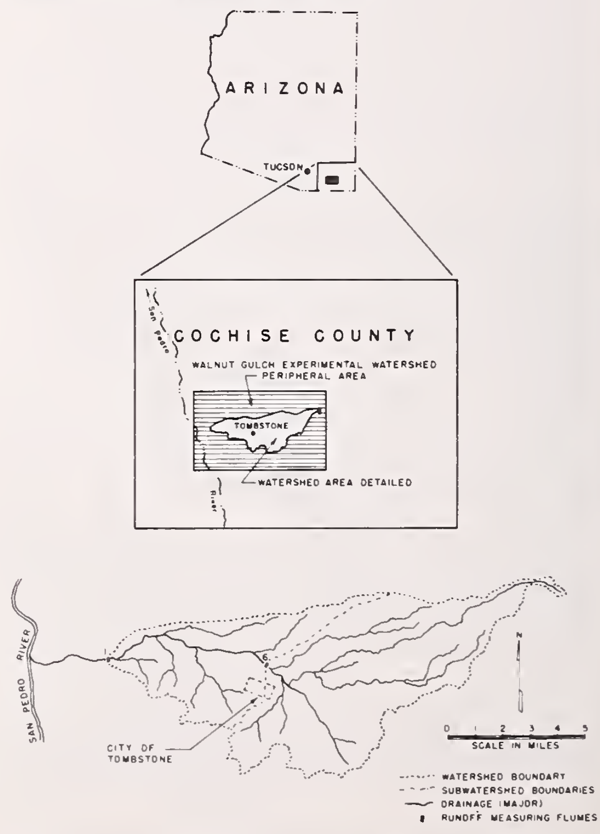

FIGURE 2.—Walnut Gulch Experimental Watershed.

TABLE 1.—*Assumed probability distributions for variables describing runoff events*

Runoff variable	Symbol	Theoretical distribution	Parameters
Start of runoff season	S	Normal	Mean, standard deviation.
Number of events at outlet per runoff season.	N	Poisson	Mean.
Begin time of each event	T	Normal	Mean, standard deviation.
Interval between events	D	Negative exponential.	Mean.
Logarithm of volume of runoff for each event.	L	Normal	Mean, standard deviation (of logarithms).

SEDIMENT-TRANSPORT MODEL

The sediment-transport part of the sediment-yield model was developed with the Manning equation and the Laursen (*17*) transport relation, given respectively as

$$V=\frac{1.49}{n}R^{2/3}S^{1/2}, \tag{1}$$

where V=average velocity in feet per second,
n=Manning's roughness coefficient,
R=hydraulic radius in feet,
and S=slope of bed in feet per foot,

and
$$\overline{C}=\sum^{p}\left[p\left(\frac{d}{y}\right)^{7/6}\left(\frac{\tau_0'}{\tau_c}-1\right)f\left(\frac{\sqrt{\tau_0/\rho}}{w}\right)\right], \tag{2}$$

where C=the mean concentration of total sediment in percent by weight,
p=bed material fraction of diameter d,
d=diameter of sediment particle in feet,
y=depth of flow in feet,
τ_0'=boundary shear stress associated with sediment diameter,
τ_0=boundary shear or tractive force at the stream bed=$\gamma y S_0$,
τ_c=critical tractive force for the beginning of sediment movement,
γ=mass weight of water in pounds per cubic foot,
ρ=density of water in slugs per cubic foot,
and w=fall velocity of sediment in feet per second.

With the Manning formula and the Strickler expression for n as a function of the sediment diameter ($n=0.034d^{1/6}$) it can be shown that

$$\tau_0'=KV^2\left(\frac{d}{y}\right)^{1/3}, \tag{3}$$

where $K=1/30$ and $d=D_{50}=\mu$, the mean grain size.

The critical tractive force was obtained by Laursen as

$$\tau_c=Cd, \tag{4}$$

where, from the Shields diagram, $4\leq C\leq 16$.

The function term in the formula can be determined graphically or by writing straight-line equations for segments of the u^*/w relationship given in Laursen's original paper. For the digital-computer solutions used subsequently, a linear interpolation scheme was developed with logarithms of the data for straight-line segments of the original graph. The fall velocity for the sediment was computed with a similar logarithmic interpolation scheme for data from figure 5 of reference 23.

The instantaneous sediment discharge (assuming a bulk dry sediment weight of 100 lb/ft^3) for a given water discharge was obtained by Laursen from the equation

$$q_s=\frac{\overline{C}q}{265}, \tag{5}$$

where q_s=instantaneous sediment discharge in cubic feet per second per foot of stream width,

q=instantaneous water discharge in cubic feet per second per foot of stream width,

and $\overline{C}$=mean sediment concentration in percent by weight.

Many ephemeral streams have wide cross sections with relatively level bottoms. Such wide sections and relatively shallow flow depths relative to the channel width allow approximating the hydraulic radius with the flow depth (y). Further simplification can be made by assuming that the flow cross section can be approximated by a rectangular section where area is the product of the top width and the flow depth, the relationship used in equation 5. With these assumptions and equations, a computer program was developed to facilitate the computations. A flow chart for this program is shown in figure 4.

To compute the sediment-discharge volume associated with each runoff event, a triangular hydrograph shape was assumed. To minimize the computing time, discharge-concentration computations were based on the value of Q_p/b, with a simple triangle assumed when Q_p/b was less than unity (b is the stream width in feet). When Q_p/b was less than 10, the concentration was obtained at the hydrograph peak and at one-half the peak value, and the resulting sediment-discharge graph was integrated to obtain the volume. Similarly, when $Q_p/b>10$, the sediment discharge was obtained for the peak discharge and at one-third and two-thirds of the peak value. This scheme preserved some of the nonlinearities involved in the sediment-discharge computations.

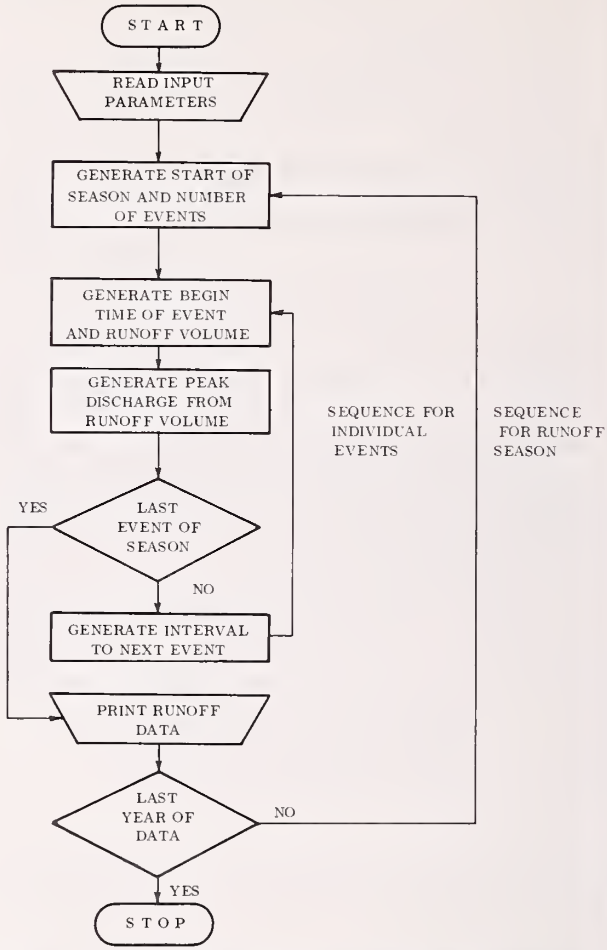

FIGURE 3.—Flow chart of synthetic data generation process. (From Lane and Renard, *16*.)

MODEL VERIFICATION

Methods for analysis and comparison of observed and synthetic runoff data from semiarid watersheds have been developed and tested (*16*). Three 50-yr sets of synthetic runoff data were generated on a 36.7-mi² subarea on the Walnut Gulch watershed and compared with the shorter sequence of observed data. Two comparisons were necessary to judge the degree of correspondence between the statistics of the actual and synthetic data for those parameters used in the generation process. This correspondence was good. Parameters not used as direct input to the model were also compared. Four such comparisons are shown on table 2. The means and standard deviations should agree, and the ranges in the longer synthetic data sets should exceed those of the shorter observed data set. Peak-discharges and length-of-season ranges satisfy this hypothesis, but annual volumes agree better. The most serious differences in table 2 are between the standard deviations of the season length for the observed and synthetic data, suggesting a need for an added constraint on season length within the model.

The comparisons between observed and synthetic runoff data indicate that the model generates data comparable to the observed data with respect to the comparison criteria (table 2), except for the variability in season length. However, the mean values of season length corre-

spond, allowing the use of this runoff model in the sediment-yield calculations. Of primary importance was the preservation of maximum annual discharge and annual runoff volume means and standard deviations.

Sediment-discharge data are difficult to obtain in ephemeral streams because (1) the flow depths change rapidly, (2) the high stream velocities make it difficult to obtain an aliquot of the water-sediment mixture by conventional depth-integrating samplers, and (3) high debris loads clog samplers and impair sampler operation. Depth-integrated samples obtained intermittently at flumes 1 and 6 on the Walnut Gulch Experimental Watershed (fig. 2) were used. Samples at these two gaging sites were obtained with a USD-48 hand sampler by wading across the stream at low discharges. At high stages, a USP-63 depth-integrating sampler was lowered from a cableway about 100 ft upstream from the flume.

Synthetic values of peak sediment discharge and storm sediment volume (suspended sediment only) are compared with actual measurements in figures 5 and 6 for the outlet of Walnut Gulch. The agreement between the actual and synthetic data is encouraging, although the snythetic

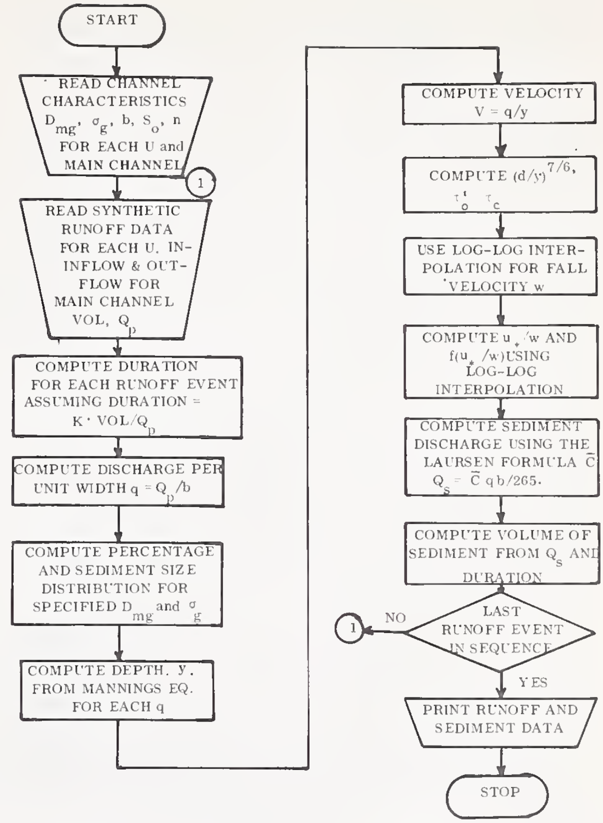

FIGURE 4.—Flow chart of sediment-discharge computation program.

TABLE 2.—*Comparison of parameters not used in generation of synthetic data*[1]

Runoff variable	Observed data (93 events)	Synthetic data Set 50-1 (605 events)	Set 50-2 (567 events)	Set 50-3 (578 events)
Peak individual discharge (ft^3/s):				
Mean	495	614	545	509
Standard deviation	1,114	1,699	1,322	1,483
Range	0–7,300	0–23,800	0–11,700	0–21,300
Maximum annual discharge (ft^3/s):[2]				
Mean	2,845	4,152	3,399	3,486
Standard deviation	2,390	4,212	2,732	3,656
Range	64–7,300	417–23,800	26–11,700	184–21,300
Annual runoff (inches):				
Mean	0.25	0.27	0.22	0.21
Standard deviation	0.24	0.21	0.18	0.16
Range	0.009–0.750	0.019–0.825	0.0002–0.670	0.017–0.852
Runoff season (days):				
Mean	59.2	64.6	60.6	60.5
Standard deviation	12.1	28.0	28.0	19.6
Range	41–80	16–137	1–150	23–118

[1] From Lane and Renard (*16*).
[2] Annual values based on 8 yr of historic data and 50-yr sets of synthetic data.

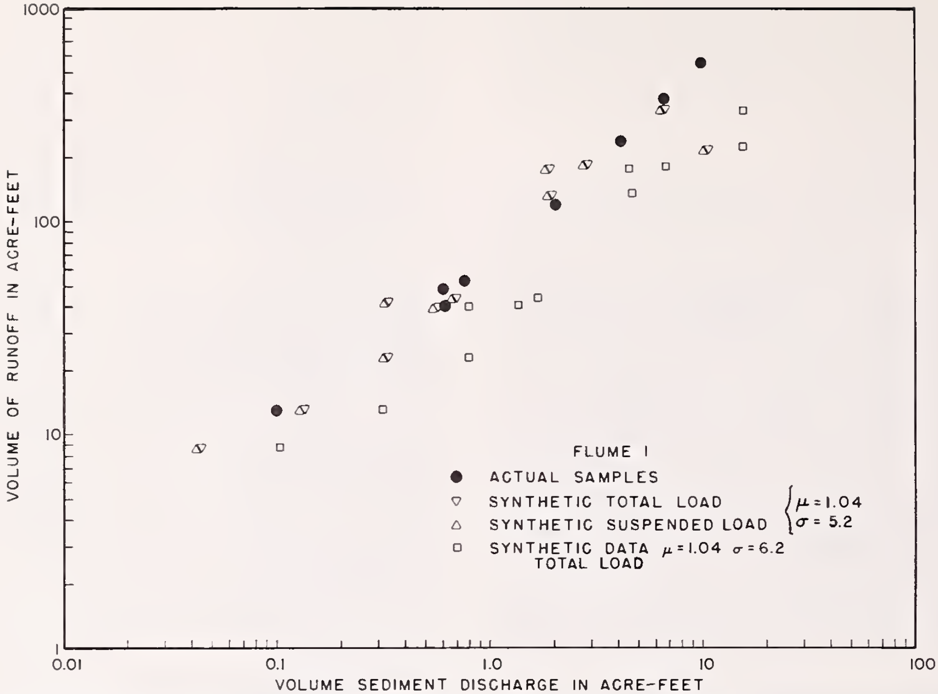

FIGURE 5.—Comparison of the synthetic and actual sediment yields for selected runoff events and bed-material size distributions by a log-normal probability relationship quantified by a mean diameter (μ) and standard deviation (σ).

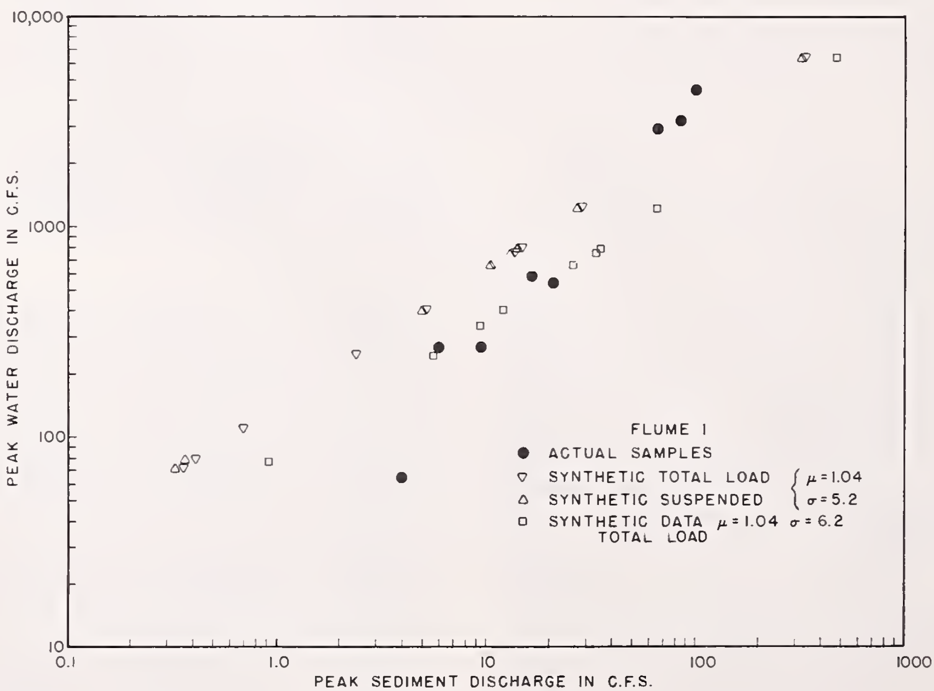

FIGURE 6.—Comparison of synthetic and actual peak sediment discharges for selected events on Walnut Gulch at flume 1 and bed-material size distributions by a log-normal probability relationship quantified by a mean diameter (μ) and a standard deviation (σ).

values are very sensitive to the bed-material size distribution represented on the figure by the mean grain size (μ) and the standard deviation (σ). The individual concentration-water discharge values, however, exhibit a wider scatter than that shown in these figures.

Figure 7 shows the concentration data for samples collected at the Walnut Gulch outlet during the 1970 summer monsoon season. As shown in this figure, the concentration for any instantaneous discharge varies considerably (almost a full log cycle). Tracing the pattern of consecutive samples for an individual flow event shows a typical "7," or loop, pattern. (See the short dash line connecting the open squares in the upper left portion of figure 7.) Thus, for example, the concentration remains essentially independent of discharge on the rising portion of the hydrograph and exhibits a more normal concentration line slope on the recession.

The lines shown on the graph are the concentration-discharge relationship for various bed-material size distributions computed by the Manning flow equation with the Laursen sediment-transport relation. The solid lines in the figure represent Manning roughness values of 0.025, and the dash lines represent roughness values of 0.020. The shaded portions illustrate the transport portion associated with the bedload as predicted from the Laursen relation for two size distributions and roughness values.

Sediment sizes of the material available for transport on the streambed vary considerably, both spatially and temporally. Figure 8 illustrates some of the variability encountered by sampling the channel material 100 ft upstream from the flume after each flow event in 1970, i.e., corresponding to the sampling periods shown in figure 7. Such sampling at equal increments across the stream showed wide variations in the mean size and some variation in the standard deviation. The log-normal distribution shown in this figure was used in the sediment concentration generating routine to obtain the percentage of material in various size increments, which simplified the computation scheme. Thus, although the extremes departed slightly from a straight-line theoretical distribution, these deviations were probably less than the errors associated with other assumptions. The importance of this size variation within a storm and within a season can be seen from the mean sediment size (μ) and the standard deviation (σ) used in figure 7 to label the individual concentration-discharge lines.

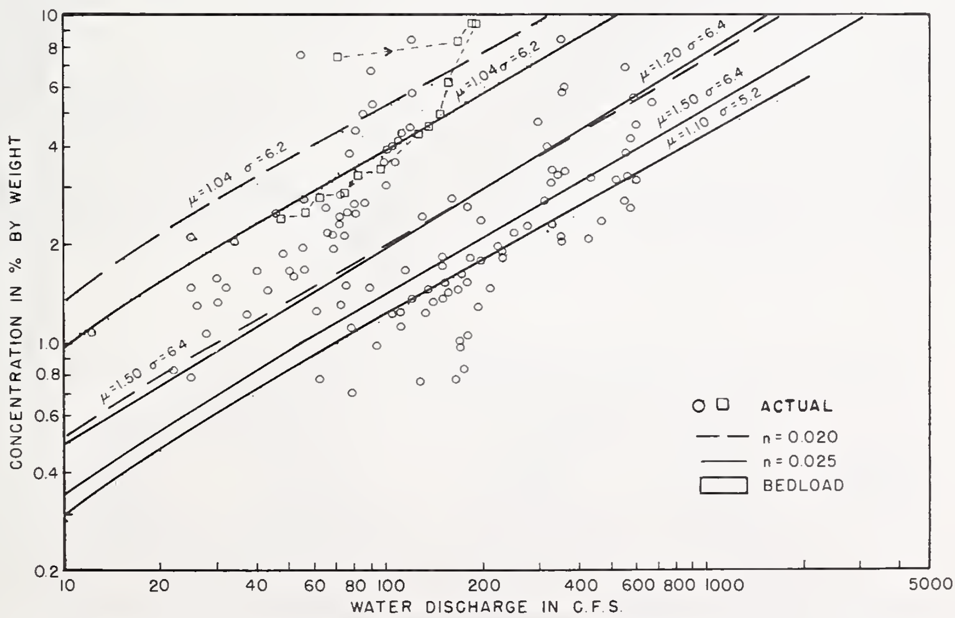

FIGURE 7.—Sediment concentration versus water discharge at flume 1 on Walnut Gulch. The circles are instantaneous values obtained by sampling in 1970, and the square connected by the dash line is a typical pattern associated with an individual runoff event. The solid and dash lines are values predicted with the Laursen transport relation for various size distributions given by the mean and standard deviations shown.

Synthetic runoff and sediment data were generated on watersheds 1 and 6. These 50-yr sets of synthetic data were formed by generating runoff data with the stochastic model described earlier and then by using these runoff data in the runoff-sediment model. The result of coupling a stochastic and deterministic model is again a stochastic sequence of runoff and sediment data.

The generation of synthetic data sequences is based on the premise that such data are adequate for predictive uses if (1) the synthetic runoff data are comparable to the actual data, (2) the runoff-to-sediment portion of the model is physically based, and (3) the synthetic sediment yield is comparable to prototype data.

Log-normal distributions were fitted to the synthetic annual runoff and sediment data generated with the model. A plot of annual runoff volumes is shown in figure 9 for 50-yr sequences of synthetic data on each of the two watersheds used in this study. The plotted points represent the synthetic runoff data and the line is a log-normal distribution fitted to the data. A similar plot for the synthetic annual sediment-yield data is shown in figure 10.

The volumes of sediment and runoff for any probability are larger for the larger watershed. This occurs even though the mean annual runoff (in inches from the watershed) was less for the larger watershed. The two theoretical lines diverge for the sediment data at the extreme.

Table 3 shows the variation in the annual runoff and sediment yield for various return periods. The annual sediment-yield data, expressed in inches, from the watersheds are surprisingly similar for each return period, although the runoffs differ. The similarity may indicate that ephemeral channels such as the Walnut Gulch channel react dynamically, adjusting the stream width and mean sediment size to maintain a quasi-equilibrium. Such a statement, however, is predicated on the assumption that the sediment size remains within limits, as shown in figure 8 and as used in the synthetic generation scheme.

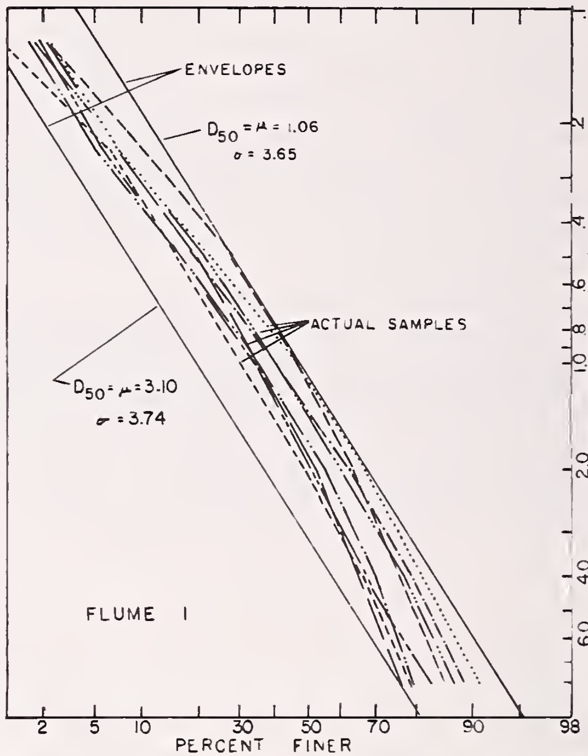

FIGURE 8.—Bed-material size distribution variation above flume 1 during the 1970 summer runoff season.

TABLE 3.—*Walnut Gulch: Return periods from 50-yr synthetic data sets*[1]

Return period (yr)	Watershed 1 (57.7 mi²) Annual runoff volume Acre-ft	Inch	Annual sediment yield Acre-ft	Inch	Watershed 6 (36.7 mi²) Annual runoff volume Acre-ft	Inch	Annual sediment yield Acre-ft	Inch
5	1,170	0.38	30	0.010	790	0.40	16	0.008
10	1,600	.52	47	.015	1,160	.59	28	.014
25	2,300	.75	76	.025	1,730	.88	51	.026
50	2,800	.91	100	.033	2,300	1.17	75	.038

[1] Based on a log-normal distribution for annual volumes.

RECOMMENDATIONS FOR FUTURE WORK

Although we believe that the model, tested on a single catchment containing several subwatersheds, is applicable to semiarid regions in the Southwest, additional work is needed to apply the model to a region. A regional model could be tied to physical and climatic characteristics, allowing synthetic runoff generation on ungaged basins where thunderstorms produce the principal runoff.

Because the sediment transport of the model appears to be so sensitive to the size distribution of the bed alluvium, efforts need to be directed to quantifying both the temporal and spatial variability of the bed material during an individual flow, as well as from one flow to another. Slight changes in the mean grain size and in the standard deviation when using a log-normal probability distribution caused major changes in the concentration predicted with the Laursen sediment-transport relationship. Such changes in the bed-material size distribution may explain the wide variability of the concentration obtained by field sampling and may allow closer agreement between the predicted and observed data.

Although a deterministic scheme was used to calculate the sediment concentration, it may be less deterministic than the runoff. Work is anticipated to let the mean (μ) and standard deviation (σ) have the characteristics of the sampled bed material with the μ and σ values randomly generated or related to the characteristics of the storm. Such a method will hopefully more adequately represent the prototype than the constant values used herein.

Subdivision of the rectangular cross section into a shape nearer that actually encountered in field conditions will facilitate quantifying variability of the flow depth and thus the water velocity and particle shear. Such an effort, however, is difficult to justify except at low discharges, since samples in the prototype are usually collected at an individual location in the cross section because of the rapid changes in the flow depth.

The sediment transport of the model is quite sensitive to the roughness value used in the Manning equation. For example, reducing the roughness from 0.025 to 0.020 had the same effect on the predicted sediment concentration as

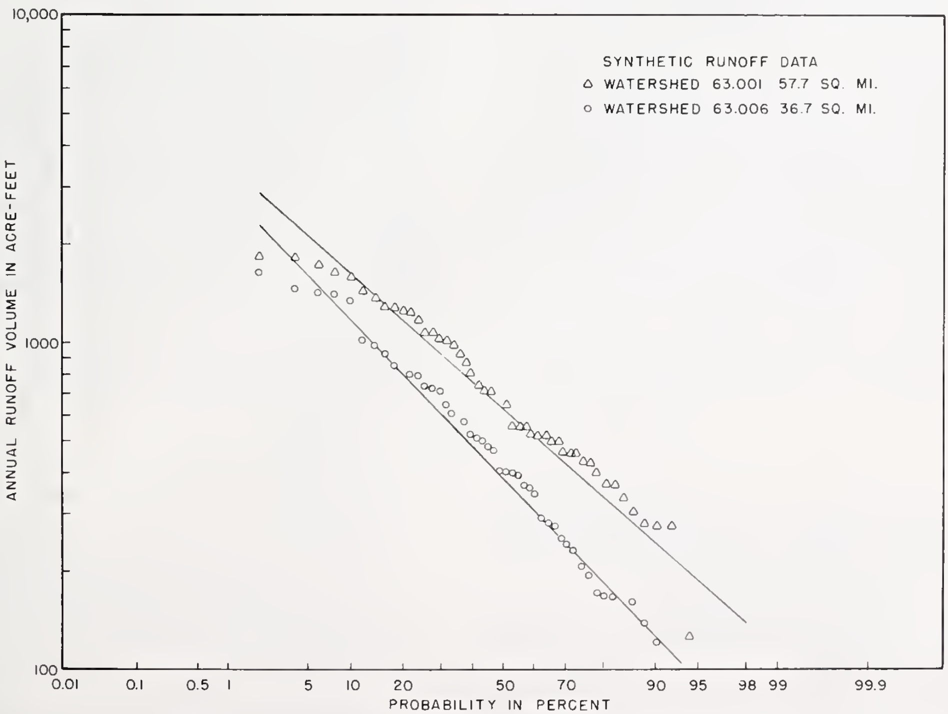

FIGURE 9.—Log-normal probability distribution for the synthetic annual runoff data from a 50-yr generated sample at two Walnut Gulch watersheds.

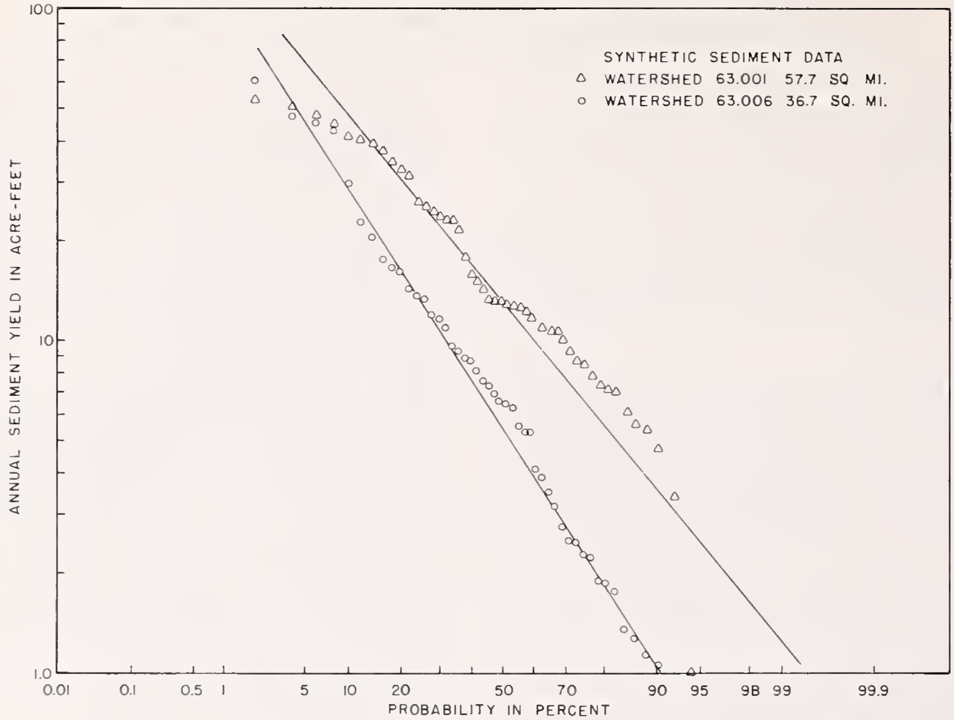

FIGURE 10.—Log-normal probability distribution for the synthetic annual sediment-yield data from a 50-yr generated sample at two Walnut Gulch watersheds.

reducing the mean grain size from 1.50 to 1.20 mm. Again, because of the difficulty of field verification, a numerical value for this parameter is difficult to obtain. Limited data in an instrumented channel reach revealed highly variable roughness values on the hydrograph rise because of the variability of transmission losses, which may absorb most of the rising portion of the hydrograph in a dry channel. At larger discharges, overriding waves tend to reduce the roughness and produce an artificially low roughness. Gross answers between tandem gaging stations indicate values approximating those used in this report, although the value at lower discharges is probably higher than the value used here. Again, braided flow and irregular cross sections make field observations difficult.

The runoff data of Walnut Gulch, which provided the numerical values used in the stochastic runoff model, are being retabulated. Eccentricities in the approach channel that are not time invariant have been modeled in a hydraulic laboratory. The results are being used to develop new prototype depth-discharge relationships. Thus, the mean and standard deviation in the normal distribution used to simulate the individual runoff event volume may change with the new information, although the changes are expected to be small compared to other assumptions used.

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WATERSHED SEDIMENT YIELD—A STOCHASTIC APPROACH[1]

By D. A. Woolhiser and P. H. Blinco[2]

INTRODUCTION

Sediment yield has been defined as "the total sediment outflow from a watershed or drainage basin, measurable at a point of reference and in a specified period of time" (*1*).[3] Estimates of watershed sediment yield are required for designing dams, debris basins, canals and other structures, and for evaluating certain land-management practices. The recent interest in sediment as a pollutant or carrier of pollutants such as radioactive materials, pesticides, and nutrients has reemphasized the importance of sediment-yield estimates. In all of these applications, the variation of sediment yield from year to year as well as the mean annual yield may be important. If we had long records of sediment yield, the annual variability could be easily evaluated. Unfortunately, records of sediment yield either are not available or are much shorter than records of streamflow or rainfall. In these circumstances we can use existing data more efficiently by constructing formal stochastic models of sediment yield that have structures dependent upon the runoff process, the rainfall process and other factors governing detachment, entrainment, transport, and deposition of sediment. Such models will provide a framework for analysis of existing short records of sediment yield and the parameters of these models may be regionalized.

According to Parzen (*8*), a stochastic process is the dynamic part of probability theory and we observe a stochastic process whenever we examine a process developing in time in a manner controlled by probabilistic laws. From this informal definition, it is clear that sediment yield can be treated as a stochastic process. However, in practice we have been concerned primarily with expected values, such as mean annual sediment yield or the expected yield in T years. Krumbein (*2*) described three stages of statistical development in sedimentology: descriptive statistics, analytical statistics, and application of stochastic process models. In descriptive statistics, the sample is of primary interest; in analytical statistics, the sample is important only for the information it contains concerning the population of interest. Analytical statistics involves the construction of formal statistical models in experimental design, and statistical inference in analysis and interpretation. In the third stage, the application of stochastic processes, formal models are constructed that describe the chance mechanisms involved in the phenomena. The stochastic model may include deterministic components developed from basic physical considerations. In such cases, the model parameters are more likely to have some physical meaning. A review of the literature on sediment yield indicates that most of the recent work is included in the second stage of statistical development (*6, 9, 11, 14*); only recently have stochastic models been considered (*5, 15*).

The purpose of this paper is to develop some preliminary models of sediment yield as a stochastic process and to demonstrate possible advantages of this approach over presently used methods.

[1] Cooperative research of the Agricultural Research Service, U.S. Department of Agriculture, and Colorado State University Experiment Station.

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[3] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this paper.

PHENOMONOLOGICAL DESCRIPTION OF SEDIMENT YIELD

Consider the general distributed model of a watershed as portrayed by figure 1. This open system is bounded by impervious rock on the bottom, by imaginary surface S on the sides, and by imaginary surface A on top. Input to the system consists of precipitation flux through surface A, which we can designate as the stochastic process $\xi_1(x,y,t)$. Output from the system includes evapotranspiration $\xi_2(x,y,t)$, porous media flow through surface $S,\eta(x,y,z,t)$, and surface streamflow which can be considered as the point process $\zeta_1(t)$.

Water erosion is initiated in several ways. Soil particles may be detached by raindrop impact or by the hydrodynamic forces of overland and channel flow. In cold climates, alternate freezing and thawing in combination with melting snow may be an important mechanism. Except for gravitational effects (creep or soil splash, for example), appreciable amounts of soil can be moved only if the rainfall intensity (or snowmelt rate) exceeds the infiltration rate of the soil, and surface runoff occurs. As the overland flow proceeds downslope, additional soil particles may be entrained if the transport capacity exceeds the sediment load, or some of the load may be deposited if the landslope becomes flatter or vegetation becomes denser. The overland flow with its load of sediment eventually enters a well-defined channel. At some cross section of the channel we can consider the sediment transport process as the point process $\{\zeta_2(t), t\varepsilon T\}$ where $\zeta_2(t)$ is the transport rate in any appropriate units and $T=\{t \geq 0\}$. The sediment-yield process $Y_2(t)$ can then be expressed as

$$Y_2(t) = \int_0^t \zeta_2(s)\,ds. \qquad (1)$$

A typical sample function of the sediment-transport process and the sediment-yield process is shown in figure 2. Sediment transport and yield from a small watershed drained by an ephemeral stream would be similar to the sample functions in the figure, while transport from a large river would be continuous rather than intermittent.

In the design of reservoirs with high trap efficiencies, we would be interested in the distribution of sediment yield in time t:

$$F_t(y) = P\{Y_2(t) \leq y\}. \qquad (2)$$

Let $T(y)$ be the minimum time required for the accumulated sediment yield to equal or exceed the amount y, or

$$T(y) = \inf\{t, Y_2(t) \geq y\}, \qquad (3)$$

which may be called the first-passage time.

The distribution function for the first-passage time is

$$G_y(t) = P\{T(y) \leq t\}. \qquad (4)$$

Now, because $Y_2(t)$ represents a stochastic process of nondecreasing sample functions $P\{T(y) > t\} = P\{Y_2(t) \leq y\}$, it follows that

$$G_y(t) = 1 - F_t(y). \qquad (5)$$

The distribution function for sediment yield in time t and the distribution function of the first-passage time of accumulated sediment yield may be useful in evaluating risks involved in design of sediment pools in reservoirs. If the trap

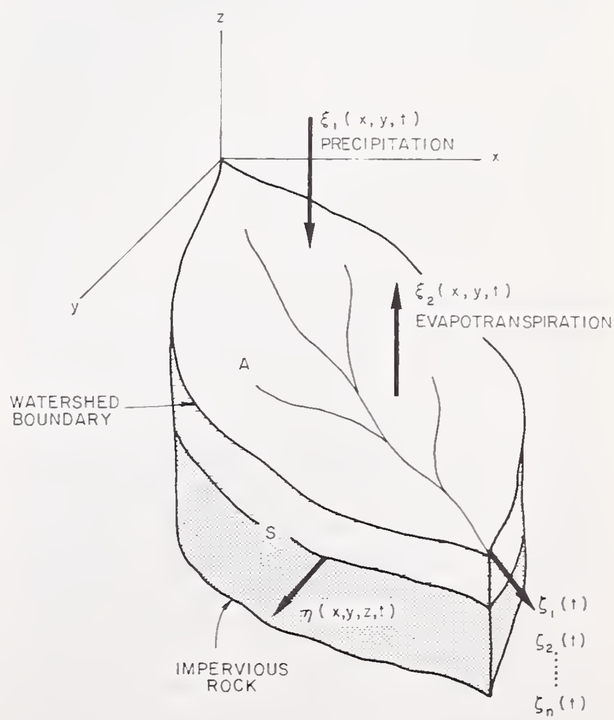

FIGURE 1.—Watershed-stochastic processes.

efficiency of the reservoir remains constant during the period of interest, the sediment accumulation is related to sediment yield rather directly. If the trap efficiency is affected by sediment accumulation, sediment yield could be treated as a sum of finite period accumulations where the trap efficiency remains constant within a period but changes instantaneously at the end of each period.

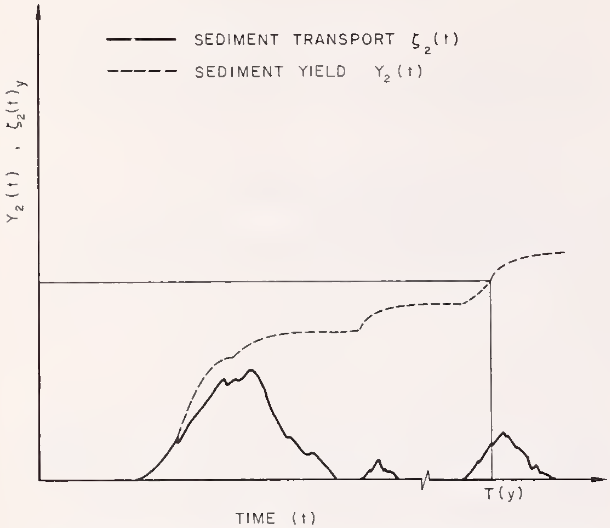

FIGURE 2.—Sample functions of the sediment-transport process $\zeta_2(t)$ and sediment-yield process $Y_2(t)$.

It is obvious that the sediment-yield process is highly dependent upon runoff, which is in turn dependent upon precipitation. It is also evident that both runoff and sediment yield are influenced by vegetation, soil, and geomorphological characteristics of a watershed.

The expressions in equations 1 through 5 apply to any situation. To develop useful descriptions of sediment yield, however, we must construct models describing the relationships between rainfall, onsite erosion, and sediment yield at the mouth of the watershed.

SOME ALTERNATIVE SEDIMENT-YIELD MODELS

The universal soil loss equation (*13*) was developed from statistical analyses of more than 10,000 plot-years of basic runoff and erosion data. Consequently, the factors that have been shown to be important in predicting the mean annual erosion loss (which is the expected value of sediment yield for 1 yr for a plot or field) should be considered in any stochastic sediment yield model. The factors involved in the universal soil loss equation are erosive potential of local rainfall; erodibility potential of specific soil; slope length; degree of slope; cover, crop sequence, and management; and conservation practices. Of these factors, rainfall erosive potential, soil erodibility, and cover are random variables for individual storms; all will vary in time and in space for areas larger than individual fields.

Let us assume that all temporal variations can be handled by considering a season length such that the parameters of the stochastic processes involved can be considered constant. The complexity of the sediment-yield model will then be dependent upon the amount of spatial variability we wish to consider. Three degrees of spatial variation are shown as cases 1–3 in table 1. Case 1 corresponds to sediment yield from a small erosion plot and is by far the simplest case. We shall first consider some of the approaches that might be used for this special case, and then consider possible extensions to more difficult cases.

If expressions for $F_t(y)$ can be obtained for each season, the distribution function for the sum of sediment yields for n seasons can be obtained by convolution, provided that we can assume independence. Thus if we let $F_{Y_i}(y)$ be the distribution function of sediment yield for the i^{th} season, the distribution for the total yield for the first two seasons is

$$F_{Y_1+Y_2}(z) = \int_0^{\infty} F_{Y_1}(z-y)\,dF_{Y_2}(y).$$

Sediment Yield From a Plot

Consider the standard fallow plot used by Wischmeier and Smith (*12*) in developing the universal soil loss equation. It is 72.6 ft long with a slope of 9 pct, and is tilled in the direction of the maximum slope. We will be concerned with the three stochastic processes $\xi_1(t)$, $\zeta_1(t)$, and $\zeta_2(t)$, which represent the rainfall rate, runoff rate, and sediment-transport rate, respectively. Sample functions of these processes are shown in figure 3. In the following, our notation will conform as closely as possible to that used by Woolhiser and Todorovic (*15*). We shall define a "rainfall event" as any continuous period of rainfall (i.e.,

TABLE 1.—*Characteristics of sediment yield models*

Sediment yield variables	Case 1: Very small watershed (plot)	Case 2: Small watershed (field)	Case 3: Large watershed
Rainfall erosive potential.	Uniform	Uniform	Spatially varied.
Soil erodibility	do	Spatially varied	Do.
Slope length	do	do	Do.
Degree of slope	do	do	Do.
Cover, management	do	Uniform	Do.
Conservation practices.	do	do	Do.
Characterstic runoff response time.	Minutes	Hours	Days.

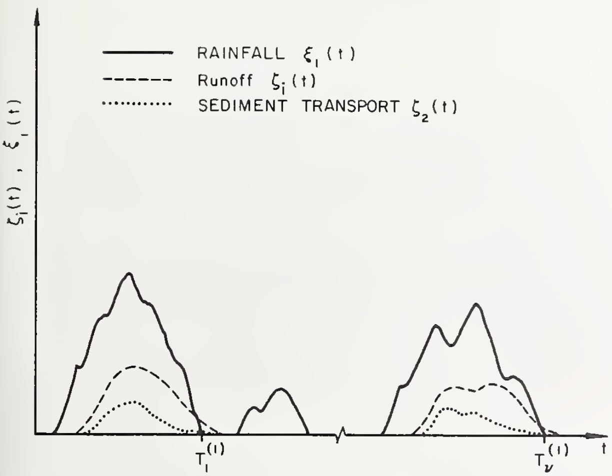

FIGURE 3.—Sample functions of the processes $\xi_1(t)$, $\zeta_1(t)$, and $\zeta_2(t)$.

$\xi_1(t)>0$). A runoff event is any continuous period of surface runoff, and we assume that a sediment yield event is associated with each runoff event.

Associated with the νth rainfall event is the time of ending $T_\nu^{(1)}$, the total volume of rainfall $X_\nu^{(1)}$, the total kinetic energy of the rainfall E_ν, and the maximum 30-min intensity I_ν. Similarly, $T_\nu^{(2)}$ refers to the time of ending of the νth sediment-yield event and runoff event and the volumes of runoff and the sediment yield are designated $Y_\nu^{(1)}$ and $Y_\nu^{(2)}$. By definition

$$X_\nu^{(1)} = \int_{T_{\nu-1}^{(1)}}^{T_\nu^{(1)}} \xi_1(s)\,ds. \tag{6}$$

$$Y_\nu^{(1)} = \int_{T_{\nu-1}^{(2)}}^{T_\nu^{(2)}} \zeta_1(s)\,ds. \tag{7}$$

$$Y_\nu^{(2)} = \int_{T_{\nu-1}^{(2)}}^{T_\nu^{(2)}} \zeta_2(s)\,ds. \tag{8}$$

The total sediment yield in the time interval $(0,t]$ can be expressed exactly as the stochastic integral of equation 1, or may be approximated by the sum

$$\underline{Y}_2(t) = \sum_{\nu=0}^{N_2(t)} Y_\nu^{(2)}, \tag{9}$$

where $N_2(t)$ is the number of complete sediment yield events in $(0,t]$. Because sediment-yield events from erosion plots are of relatively short duration, the probability of having $\zeta_2(s)>0$ for $s\epsilon(T_{N_2(t)}^{(2)}, t]$ is rather small, so equation 9 is a good approximation of equation 1 for t in the order of weeks. If we assume that the number of sediment events in $(0,t]$ is independent of the magnitude of the events, the distribution of sediment yield in $(0,t]$ can be written

$$F_t(y) = P\{Y_2(t) \le y\} = P\{N_2(t)=0\} + \sum_{\nu=1}^{\infty} P\{Z_\nu \le y\} P\{N_2(t)=\nu\}, \tag{10}$$

where $$Z_\nu = \sum_{i=1}^{\nu} Y_i^{(2)}.$$

The mean and variance are given by the following well-known expressions (*8*):

$$E\{\underline{Y}_2(t)\} = E\{N_2(t)\} E\{Y^{(2)}\} \qquad (11)$$

$$\mathrm{Var}\{\underline{Y}_2(t)\} = E\{N_2(t)\}\,\mathrm{Var}\{Y^{(2)}\} + \mathrm{Var}\{N_2(t)\} E^2\{Y^{(2)}\}. \qquad (12)$$

From equation 10 we see that we must develop an expression for the sediment-yield counting process $N_2(t)$ and the distribution of the sum of ν sediment-yield events in order to specify the distribution of sediment yield.

Although he used a different definition of rainfall events than we use, Wischmeier (*11*) found that the sediment yield per event is highly correlated with the product of total rainfall kinetic energy and maximum 30-min intensity for storms greater than 0.5 inch. This suggests that the sediment yield per storm can be expressed as the sum of two random variables:

$$Y_\nu^{(2)} = K(E_\nu I_\nu - m) \qquad (13)$$

$$+ \varepsilon_\nu Y_\nu^{(2)} > 0,$$

where ε_ν is an independent, normally distributed random variable with mean zero and variance σ^2.

Equation 13 suggests that there exists some threshold level of the product EI below which no erosion occurs. Let us suppose for example that $E_\nu I_\nu$ is an independent, identically distributed random variable with exponential distribution function

$$F_{EI}(x) = P\{EI \leq x\} = 1 - e^{-\lambda x}, x > 0. \qquad (14)$$

Given the relationships of equations 13 and 14, we wish to find the density function of $Y^{(2)}$.

First define the random variable X_1:

$$X_1 = K(E_\nu I_\nu - m) + \varepsilon_\nu$$
$$-\infty < X_1 < \infty. \qquad (15)$$

Let the joint density function of X_1 and the product of kinetic energy and maximum 30-min intensity be designated as $f_{X_1,EI}(x_1,x_2)$.

The joint density is

$$f_{X_1,EI}(x_1,x_2) = f_{X_1}(x_1 | EI = x_2)\, f_{EI}(x_2), \quad (16)$$

where $f_{EI}(x_2) = \frac{d}{dx_2} F_{EI}(x_2)$ and $f_{X_1}(x_1 | EI = x_2)$ is the conditional density function, which from our earlier assumption of independence and normality can be expressed as

$$f_{X_1}(x_1 | EI = x_2) = \frac{1}{\sigma\sqrt{2\pi}} \exp$$
$$\{-(\frac{x_1 + Km - Kx_2}{\sqrt{2}\sigma})^2\}; -\infty < x_1 < \infty. \qquad (17)$$

The joint density function can thus be written as

$$f_{X_1,EI}(x_1,x_2) = \frac{1}{\sigma\sqrt{2\pi}} \exp$$
$$\{-(\frac{x_1 + Km - Kx_2}{\sqrt{2}\sigma})^2 \cdot \lambda \exp\{-\lambda x_2\}. \qquad (18)$$

The marginal density function of x_1 can be obtained by integrating the joint density function:

$$f_{X_1}(x_1) = \int_0^\infty f_{X_1,EI}(x_1,x_2)\, dx_2. \qquad (19)$$

The marginal density function of sediment yield $g_Y(y)$ can be obtained by truncating $f_{X_1}(x_1)$:

$$g_Y(y) = \frac{f_{X_1}(y)}{\int_0^\infty f_{X_1}(x_1)\, dx_1}; 0 < y < \infty. \qquad (20)$$

After some algebraic manipulation, the marginal density function of x_1 can be written

$$f_{X_1}(x_1) = \frac{\lambda}{\sqrt{\pi}K} \exp\{\frac{1}{2\sigma^2}(-x_1 + Km)$$
$$+ (-Km + \sigma^2\lambda/K - x_1)^2\} \int_{c(x_1)}^\infty \exp\{-z^2\} dz, \quad (21)$$

where $c(x_1)=\dfrac{1}{\sqrt{2}K\sigma}(-K^2m+\sigma^2\lambda-Kx_1)$.

The density function $g_Y(y)$ can be readily obtained by numerical methods utilizing equations 20 and 21.

Of the four parameters in equation 21, the parameter λ is related to the distribution of EI while σ, K, and m can be approximated from a regression of Y on EI. Some sample density functions for $g_Y(y)$ are shown in figure 4. It is worth noting that when the lower limit of integration $c(x_1)$ approaches $-\sqrt{2}$, the integral

$$\int_{c(x_1)}^{\infty} e^{-z^2}\,dz$$

becomes nearly constant; thus $g_Y(y)$ approaches an exponential distribution with parameter λ/K. Note that the density function with parameters $K=0.1$, $\lambda=0.05$, $m=15$ and $\sigma=1$ in figure 4 very nearly coincides with an exponential distribution with parameter λ/K.

Referring to equation 10, the distribution function for the sum of ν independent, sediment-yield events distributed as $g_Y(y)$ can be expressed as

$$F_\nu(z)=P\{Z_\nu\leq z\}=\int_0^z g_Y(y)^{\nu*}\,dy, \qquad (22)$$

where $g_Y(y)^{\nu*}$ indicates the νth convolution of $g_Y(y)$ with itself.

If, as in some of the examples, $g_Y(y)$ is exponential, then the νth convolution of $g_Y(y)$ is a gamma distribution:

$$g_Y(y)^{\nu*}=f_Z(z)=\lambda^\nu\,\frac{z^{\nu-1}e^{-\lambda z}}{\Gamma(\nu)}.$$

The sediment yield event-counting process in equation 10, $N_2(t)$, is defined as

$$N_2(t)=\sup\{\nu;T_\nu^{(2)}\leq t\};t\geq 0. \qquad (23)$$

Under certain assumptions the rainfall-counting process can be described by the time-dependent (nonhomogeneous) Poisson process (*10*). If runoff and sediment-yield events were chosen at random from rainfall events, the process $N_2(t)$ would also be Poissonian

$$P\{N_2(t)=n\}=\exp\{-\Lambda_2(t)\}\{\Lambda_2(t)\}^n/n!, \qquad (24)$$

where $\Lambda_2(t)$ is the expected value function defined as

$$\Lambda_2(t)=\int_0^t \lambda_2(s)\,ds,$$

where $\lambda_2(s)$ is the intensity function. Because we are considering seasons, $\lambda_2(s)$ can be consid-

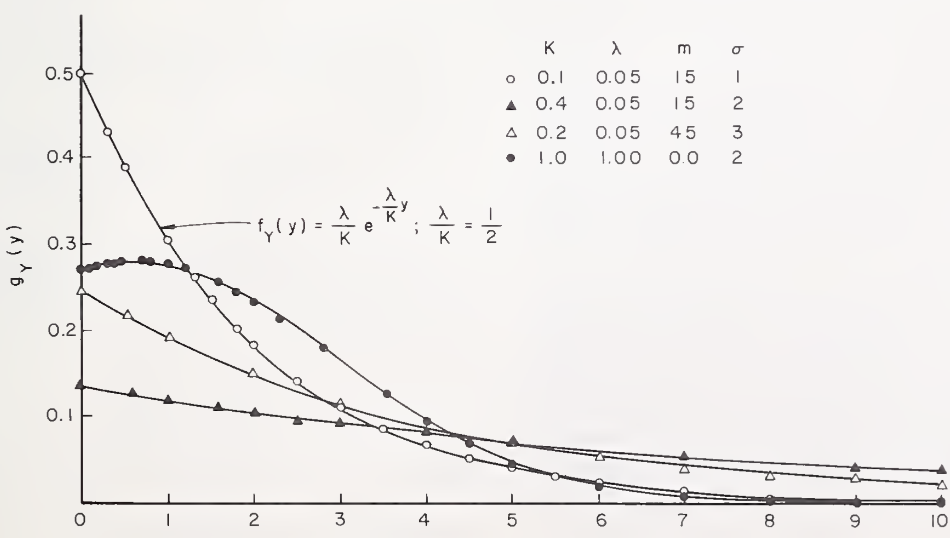

FIGURE 4.—The density function $g_Y(y)$.

ered constant. Utilizing equations 22, 24, and 10 we obtain the expression for the distribution function of sediment yield in $(0,t]$:

$$F_t(Y)=\exp\{-\lambda_2 t\}+\sum_{\nu=1}^{\infty} e^{-\lambda_2 t}\frac{(\lambda_2 t)^{\nu}}{\nu\ !}$$

$$\int_0^z g_Y(y)^{\nu *}\,dy. \tag{25}$$

Woolhiser and Todorovic (*15*) demonstrated that the above formulation of the sediment-yield counting process corresponds to either a constant or random threshold model for runoff. They proposed two alternatives: the general threshold model and the infiltration model, but could not obtain analytical results for the counting process $N_2(t)$. However, they proposed an approximation whereby runoff events are selected from rainfall events by a binomial process with parameter π which is itself beta-distributed. Under these assumptions they derived the following expression for the counting process:

$$P\{N_2(t)=\nu\}=\exp(-\lambda_1 t)\sum_{n=\nu}^{\infty}(\lambda_1 t)^n$$

$$\frac{\left[{n-\nu+\beta \atop n-\nu}\right]\left[{\nu+\alpha \atop \alpha}\right]}{\left[{n+\alpha+\beta+1 \atop n}\right]}. \tag{26}$$

They pointed out that the parameters α and β may be related to soil properties because as $\beta\rightarrow-1$, $E\{N_2(t)\}\rightarrow E\{N_1(t)\}$ or the watershed is impervious; as $\beta\rightarrow\infty, E\{N_2(t)\}\rightarrow 0$ and no runoff occurs. Woolhiser and Todorovic (*15*) found that the counting process given by equation 26 gave a much better fit to data from two small watersheds near Hastings, Nebr., than did the Poisson process.

The set of hypotheses concerning the plot erosion process embodied in equation 10 and the more restrictive expression of equation 25 must be tested with field data before they can be accepted. It appears desirable to work with fallow plots first. If the stochastic model can describe erosion satisfactorily for this case, attempts should be made to extend it to cropped plots.

Sediment Yield From a Small Watershed

We will now consider the more complicated situation of case 2 in table 1. This corresponds to a watershed on the order of a few acres in size. The rainfall erosive potential, the cover and management, and the conservation practices are uniform, but the other factors affecting soil loss vary from point to point within the watershed. Because this problem is very complex, a great deal of simplification is required to construct a model. Consider the schematic drawing of the very small watershed in figure 5. We assume that the watershed boundary lies within the field boundaries and that there is a definite drainage pattern. Each point within the watershed is characterized by its translation time τ to the outlet. Although translation time is dependent on runoff rates, we will consider it at some characteristic runoff rate and ignore the variability. The locus of all points on the watershed with the same translation time is called an isochrone. The length of the isochrone is $dA/d\tau$ when A is surface area. Let $s_\nu(\tau)$ be the average weight of soil eroded per unit area along an isochrone during the νth event. Finally let $p(\tau)$ be the probability that a soil particle eroded along an isochrone will reach the mouth of the watershed during the same event. The total erosion during the νth event is then

$$X_{\nu^{(2)}}=\int_0^{\infty} s_\nu(\tau)\,\frac{dA}{d\tau}\,d\tau. \tag{27}$$

The expected sediment yield is

$$Y_{\nu^{(2)}}=\int_0^{\infty} p(\tau)\,s_\nu(\tau)\frac{dA}{d\tau}d\tau. \tag{28}$$

For an elementary example, let us suppose that $dA/d\tau$, $s_\nu(\tau)$ and $p(\tau)$ are the functions shown in figure 6. Thus,

$$\frac{dA}{d\tau}=\tau, 0\leq\tau\leq 1 \tag{29}$$

and $$s_\nu(\tau)=\tau \quad 0\leq\tau\leq 1, \tag{30}$$

where $$s_m=K(EI_\nu-m)+\varepsilon_\nu$$

and $\qquad P(\tau)=1-\tau, 0 \leq \tau \leq 1. \qquad (31)$

Thus the sediment yield from the νth event is

$$Y_\nu^{(2)}=\int_0^1 [K(EI_\nu-m)+\varepsilon_\nu]\tau^2(1-\tau)\ d\tau$$

$$=\frac{1}{12}[K(EI_\nu-m)+\varepsilon_\nu] \qquad (32)$$

and the total erosion is

$$X_\nu^{(2)}=\int_0^1 [K(EI_\nu-m)+\varepsilon_\nu]\tau^2 d\tau$$

$$=\tfrac{1}{3}[K(EI_\nu-m)+\varepsilon_\nu]. \qquad (33)$$

The sediment delivery ratio $Y_\nu^{(2)}/X_\nu^{(2)}$ is then equal to 1/4.

From an examination of equation 33 we see that as a consequence of our assumptions, the sediment yield per event for a fallow field can be expressed as the product of a constant and the sediment yield for a standard fallow plot. This constant depends on the watershed geometry and the soil variation on the watershed, which are described by the functions $dA/d\tau$, $s_\nu(\tau)$, and $p(\tau)$. The function $dA/d\tau$ can be obtained fairly easily by choosing a steady-state discharge per unit area and estimating channel and overland flow velocities. The functions $s_\nu(\tau)$ and $p(\tau)$ can be evaluated by sampling experiments, using the mathematical model of soil erosion described by Meyer and Wischmeier (*4*). If, as in the example, the functional form of $s_\nu(\tau)$ remains constant from event to event but one parameter is a random variable (s_m in the example) it seems quite likely that analytical results can be obtained for the distribution of sediment yield per event. Utilizing equation 10, the distribution function of sediment yield per season could be obtained either analytically or by numerical methods, depending upon the complexity of the counting process and the distribution of s_m.

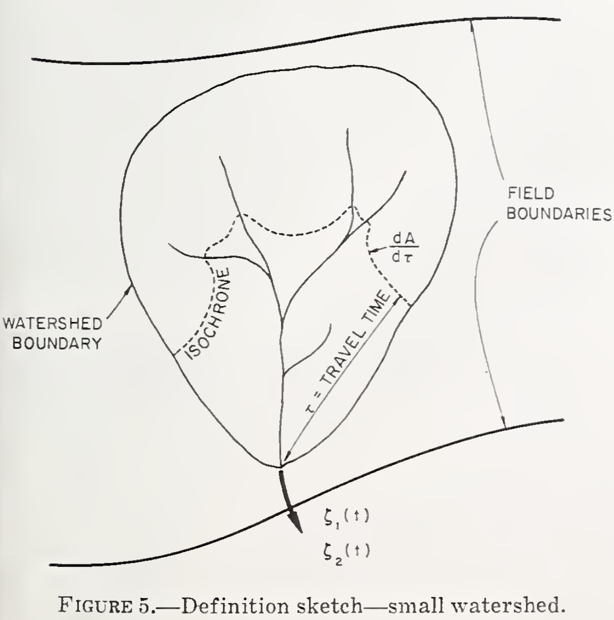

FIGURE 5.—Definition sketch—small watershed.

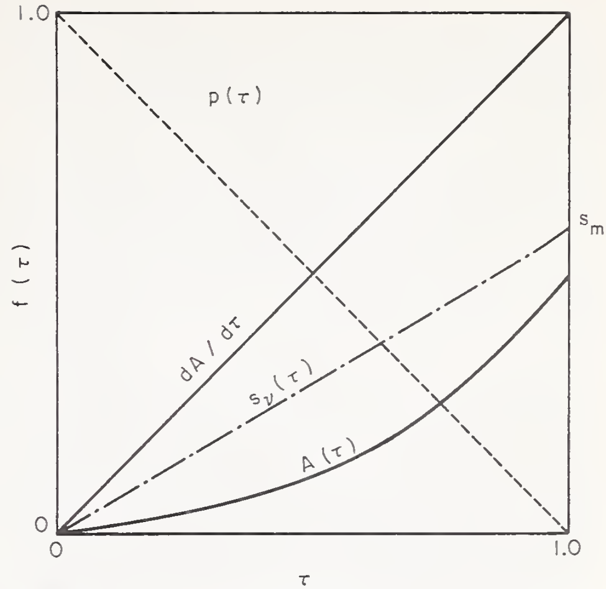

FIGURE 6.—Simplified form of $p(\tau)$, $S_\nu(\tau)$, and $dA/d\tau$, for example.

Sediment Yield From a Large Watershed

If we consider the characteristics of large watersheds shown in table 1, we see that all of the factors affecting sediment yield have significant spatial variations and that the characteristic runoff response time is in the order of days. Streamflow and sediment transport at the mouth of the watershed may occur continuously, but surface runoff and erosion within the watershed will be intermittent. McGuinness, Harrold, and Edwards (*3*) have shown that substantial differences exist between the temporal patterns of sediment yield from 1- to 2-acre watersheds as compared with the suspended-sediment yield of a 6,000-mi² watershed. Monthly sediment yield

from the small watersheds correlated well with the product of EI and a cover factor, whereas monthly suspended sediment transport from the 6,000-mi^2 watershed was correlated with the river flow and was unrelated to the precipitation pattern. This observation suggests that in climates similar to Ohio, much of the sediment eroded from upland watersheds during locally intense summer rainstorms is deposited in the major channel system where it is subsequently eroded by increasing discharges of late winter and spring.

Because of the complexity of the problem and the present primitive state of the art in applying formal stochastic models to sediment yield, we believe that it is premature to consider possible models for sediment yield from large watersheds. Such formulations should await success in describing the stochastic structure of sediment yield from plots and small watersheds. (We agree with the admonition that if you can't solve a simple problem, it is very unlikely that you can solve a more complex problem.) The problem of complexity can be dealt with in two ways: by highly simplifying the sediment yield process or by abandoning the analytic approach and using a computer simulation.

Murota and Hashino (*5*) developed a stochastic model of transported sediment for the Arita River in Japan. This model included the following components: (1) a stochastic model of daily rainfall with seasonally varying parameters; (2) a deterministic relationship between rainfall and runoff; (3) a unit hydrograph procedure to distribute runoff amounts in time; and (4) Brown's sediment-discharge formula to compute sediment-transport rates from stream-discharge rates. Although highly simplified, their model required a numerical solution on a computer to obtain the distribution of sediment yields. It appears that the time pattern of sediment yield in this model would correspond closely to the time pattern of runoff as observed by McGuinness et al., provided the rainfall-runoff relationship changed with seasons.

The simulation approach is exemplified by the work done at Stanford University (see for example, Negev, *7*). Because the simulation approach will be discussed by other papers in this workshop, we only mention it.

SUMMARY AND DISCUSSION

The sediment-yield process, from an erosion plot, a field, or a watershed, is stochastic in the sense that we can make only probabilistic statements regarding future sediment yield. Although the stochastic nature of sediment yield has been recognized implicitly for a long time, in practice we have been concerned primarily with expected values; mean annual sediment yield or the expected yield in T yr.

The useful life of sediment-detention structures and reservoirs is a random variable dependent upon sediment yield and reservoir trap efficiency. The distribution of reservoir life can be an important consideration in design. Some idea of the variability of sediment yield is also required if we wish to ask the question, "What is the probability that an observed amount of sediment could have accumulated in a reservoir if the expected value is $E\{\underline{Y}_2(t)\}$?" If the observed value has a very low probability of occurrence, we may wish to modify our estimate of $E\{Y_2(t)\}$ for the region.

In this paper we have developed mathematical expressions for the distribution function of sediment yield $F_t(y)$ for a standard fallow erosion plot and a fallow field. These models consist of a set of hypotheses regarding the process of detachment, entrainment, transport, and deposition of sediment. These hypotheses must be tested with field data, although experiments utilizing deterministic mathematical erosion models may also be useful.

Because of the complexity of the problem, research on stochastic models of sediment yield should progress from plots to fields to small watersheds.

ACKNOWLEDGMENT

V. P. Singh assisted in some of the mathematical developments.

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SEDIMENT EROSION-TRANSPORT-DEPOSITION SIMULATION: STATE OF THE ART

By George Fleming[1]

INTRODUCTION

The term "simulation" is defined in this paper as the development of mathematical models to represent the time-variant interaction of physical processes (*7*).[2] A question often posed is, "Why the need for simulation?" The simple answer is that we need to integrate the component theories affecting watershed response in order to realistically take account of the complex interrelationship among processes that are the cause of that response. Simulation is a tool by which the building blocks of component hydrological and sediment theory can be combined into a structure logically representing the concepts of both the hydrological cycle and the sediment erosion-transport-deposition chain.

Consider the problem of water resources assessment to meet the requirements imposed by man. A schematic representation of the problem is shown on figure 1. On the one side is the problem of assessing the range in magnitude of the various hydrological, sediment erosion-transport-deposition, and water-quality processes. The ability to simulate the hydrological processes is prerequisite before it is possible to simulate the sediment or water-quality processes. On the other side are the social-political-economic conditions that, acting together, result in water-resources requirements. Planning involves making the optimum policy decision on future projects to satisfy these demands, based on a knowledge of the magnitude and range of resources available.

The initial step in assessment is the analysis of available data. These data take the form of inputs to and outputs from the study watershed. Methods of analysis have been developed which can be generally classed under the heading "mathematical models." A mathematical model is defined as an abstract system interrelating in a given time reference a sample of input; cause or stimulus of matter, energy, or information; and a sample of output, effect or response of information, energy or matter. Figure 2 shows the mathematical model concept. Simulation is one form of mathematical modeling. It is a deterministic method of analysis and is shown schematically along with other techniques in figure 3. These methods generally fall into two groups: optimization methods and nonoptimization methods. The optimization methods of mathematical modeling are concerned with the selection of the best set of conditions to satisfy a set of objectives for a given set of constraints. Nonoptimization methods in mathematical modeling consist of the technique where the response of a system is analyzed for particular sets of data. As reported by Dooge (*8*) the analysis problem involves three parts (table 1). The nonoptimization methods involve one or another of these problems. Included in the group of nonoptimization methods are the deterministic and statistical methods of analysis.

In any state-of-the-art review of sediment erosion-transport-deposition simulation, it is necessary to consider the subdivisions in the above methods in order to avoid confusion in terminology. The deterministic techniques fall into the two categories, empirical/component methods and conceptual methods. The statistical methods include regression and correlation analysis, probabalistic analysis, and stochastic methods. Table 2 shows examples of the various component, conceptual, and statistical sediment models. The development of methods of analysis of sediment processes runs parallel to the methods of

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[2] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this paper.

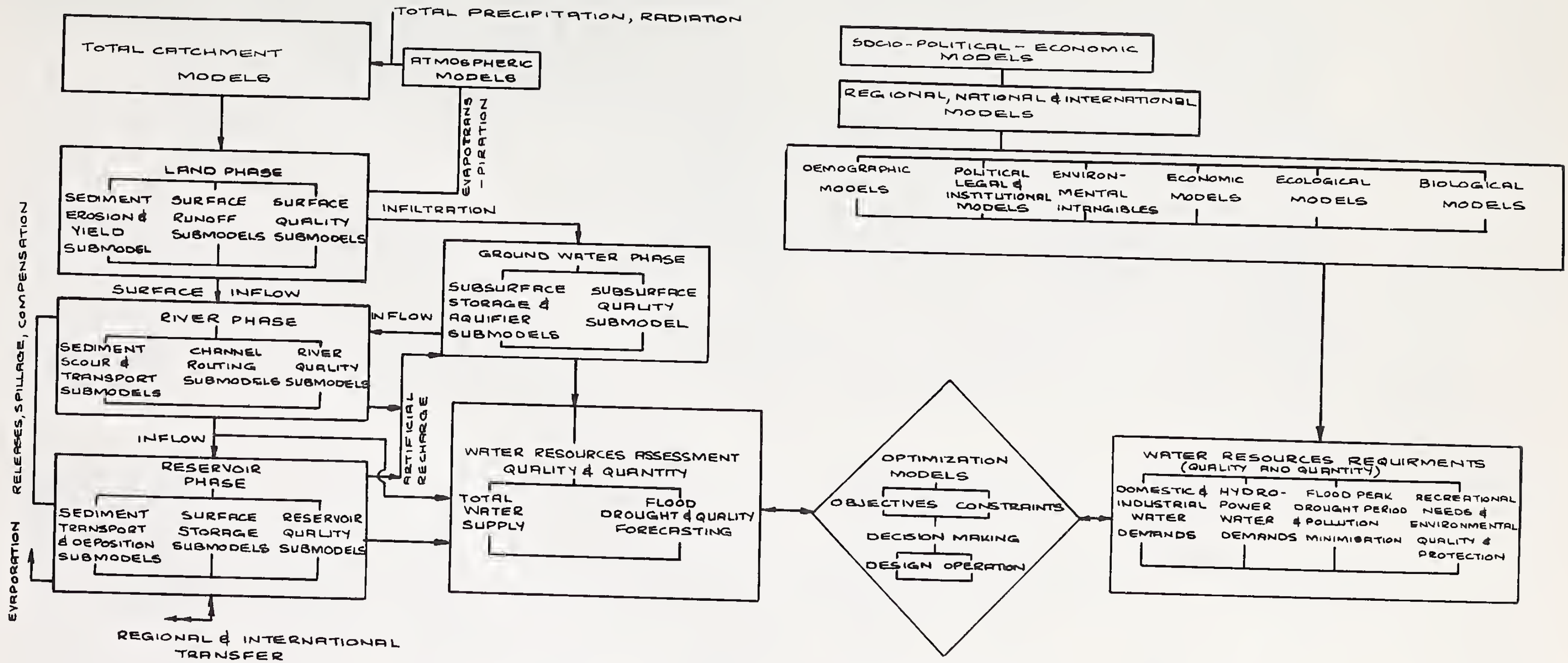

FIGURE 1.—Water resources assessment and requirement.

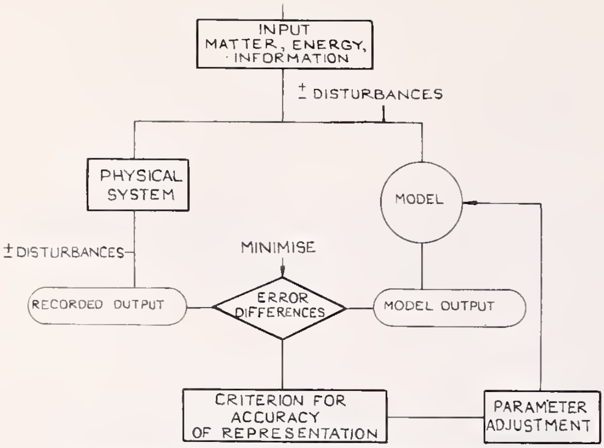

FIGURE 2.—The mathematical model concept.

hydrological processes. Component theories have been developed over the years to represent facets of the total catchment problem. This has been satisfactory in the past, where the problems have not required a comprehensive treatment. With the growth in population and the increased use of land and water resources, the problem of integrated watershed development and management

TABLE 1.—*The analysis problem*[1]

	Input	System	Output
Prediction	√	√	?
Identification	√	?	√
Detection	?	√	√

[1] After Dooge (*8*).

has arisen, which requires more sophisticated assessment and analysis techniques.

It is seen from table 2 that considerable work has been carried out on the empirical and component methods of analysis of the sediment processes together with regression and correlation analysis. Some work has been done on conceptual simulation models for one or other of the processes of erosion-transport or deposition, but no comprehensive model has yet been developed which simulates the entire chain of processes. Unlike the case of hydrological research, little use has been made of probability theory or stochastic theory as applied to sediment processes with the exception of Einstein (*10*) and Sakhan, Riley, and Renard (*25*). This is primarily due to the lack of comprehensive field data.

SIMULATION TECHNIQUES

The development of simulation techniques in hydrology is now well established with many different models in existence. The status of sediment simulation is as yet in its infancy. Models already developed or partly developed include the Negev model (fig. 4), the ARS upland erosion model (see paper by Foster and Meyer in this publication), the U.S. Army Corps of Engineers scour and deposition model (*28*) and the Hydrocomp hydrology and sediment model. A research program funded by the British Natural Environment Research Council is also underway at Strathclyde University to study mathematical model development. The ARS and Corps of Engineers models are discussed specifically in other papers presented at this workshop and hence will not be discussed here.

Negev's model is a simulation of the suspended-load component based on a conceptual structure of the fluvial erosion process. Initially rainfall impinging on the land surface is divided into two parts, that falling on impervious surfaces, and that falling on pervious surfaces. The sediment supply from impervious surfaces is computed by a power-function relationship, taking hourly rainfall as the independent variable. Fain falling on the soil is assumed to loosen material by raindrop splash. This loosened material, called soil splash, is then considered as potential sediment for the stream. If overland flow occurs as computed by the Stanford watershed model or the Hydrocomp simulation program, then all the soil splash material in previous storages is transported together with the current soil splash material.

Overland flow is also used to compute the rate of rill and gully erosion, again using a power-function relationship. Rill and gully erosion then divides into interload and bed material storage.

Input to this model consists of hourly and daily recorded rainfall, daily recorded flow and sediment load, hourly overland flow, a translation histogram for routing the sediment through the stream system, information on the sediment-rating curve for use in adjusting the material assigned to interload and bed-material load from the rill and gully process, and a set of parameters and exponents for use in the various power functions by which the sediment erosion processes are estimated. These are adjusted during test

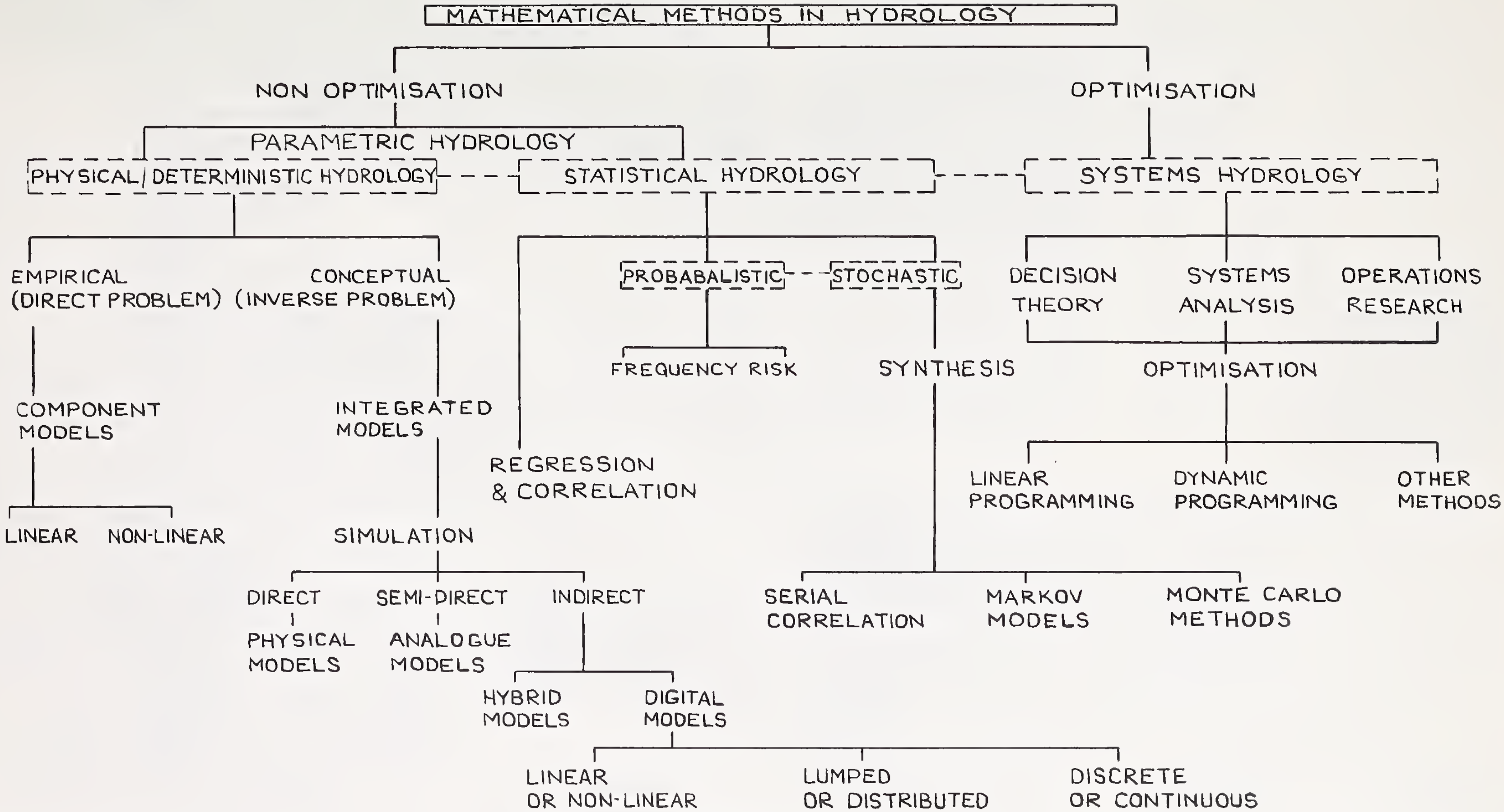

FIGURE 3.—Mathematical methods in hydrology.

TABLE 2.—*Examples of models for sediment processes*

Process	Empirical/component method	Conceptual simulation	Statistical: Regression/correlation	Statistical: Probabalistic	Statistical: Stochastic
Erosion	Horton (*18*), sheet erosion equation. ARS (*32*), universal soil loss equation. Musgrave (*23*), soil loss equation. Ellison (*11*), soil splash equation. Dragoun (*9*), sheet erosion equation.	Negev (24), sediment-erosion-transport model. ARS upland erosion model Hydrocomp (*19*), simulation programing.	Anderson (*2*), sediment-yield equation. Fleming (*14*), suspended-load design curves. SCS (*27*), gully erosion equation. Beer and Johnson (*3*), gully growth equation. Thompson (*29*), gully advance equation.	Frequency analysis of sediment-yield transport and deposition.	....
Transport	Schulits (*26*), computer programs for bedload formulas. Du Boys (*5*), transport formula. Einstein (*10*), bedload function. Colby (*6*), modified Einstein method. Blench (*4*), regime equation Laursen (*21*), transport theory. Inglis-Lacey (*20*), transport formula. Toffaleti (*30*), transport formula.	....	Sediment-rating curves	....	Random generation of sediment data. Sakhan, Riley, and Renard (*25*), simulation of sediment transport with stochastic transfer at the streambed.
Depostion	Fall velocity theory Sediment suspension/deposition theory. Density current theory Ackerman and Corinth (*1*), reservoir sedimentation equation.	Thomas (*28*), U.S. Army Corps of Engineers reservoir sedimentation model.	Farnham, Beer, and Heinemann (*12*), regression analysis of reservoir sedimentation. Stall and Bartelli (*27*), correlation of reservoir sedimentation and watershed factors.	Einstein (*10*), bedload function.	....

runs to calibrate the model to match recorded sediment load. They consist of the following:

KGER Rill and gully erosion parameter.
OGER Overload flow exponent in rill and gully function.
KRER Soil splash parameter.
ORER Rainfall exponent in soil splash function.
KSER Soil splash pickup parameter.
OSER Overland flow parameter in soil splash pickup function.
KIMP Fraction of impervious area to total watershed area.

Results obtained by Negev when he applied his model to the Napa River, St. Helena, Calif., are shown in figure 5 and indicate a good comparison between simulated and recorded loads. In 1967 both the Stanford watershed and Negev sediment models were translated and tested by the author on the River Clyde in Scotland (*13*). The simulated flows obtained from the watershed model gave a good comparison with the recorded streamflows (*15*). The results from the sediment model could only be compared with daily sediment-load estimates obtained from continuous sediment-concentration measurements indicated differences between the two methods, as shown in figure 6. It is evident that the concept of sediment transport being related exclusively to stream discharge yields a different result from the concept of sediment erosion and transport being related to rainfall, overload flow, and stream discharge. With the lack of adequate data on the River Clyde to rigorously test and compare the results of the sediment model, final conclusions could not be made regarding its applicability to that watershed.

The results of the Clyde study, however, did conclude that the Negev sediment model is essentially an erosion process model relying largely on power functions to define the relationships between processes. It represents an initial step toward the goal of an integrated model representing the complete sediment processes of erosion-transport-deposition.

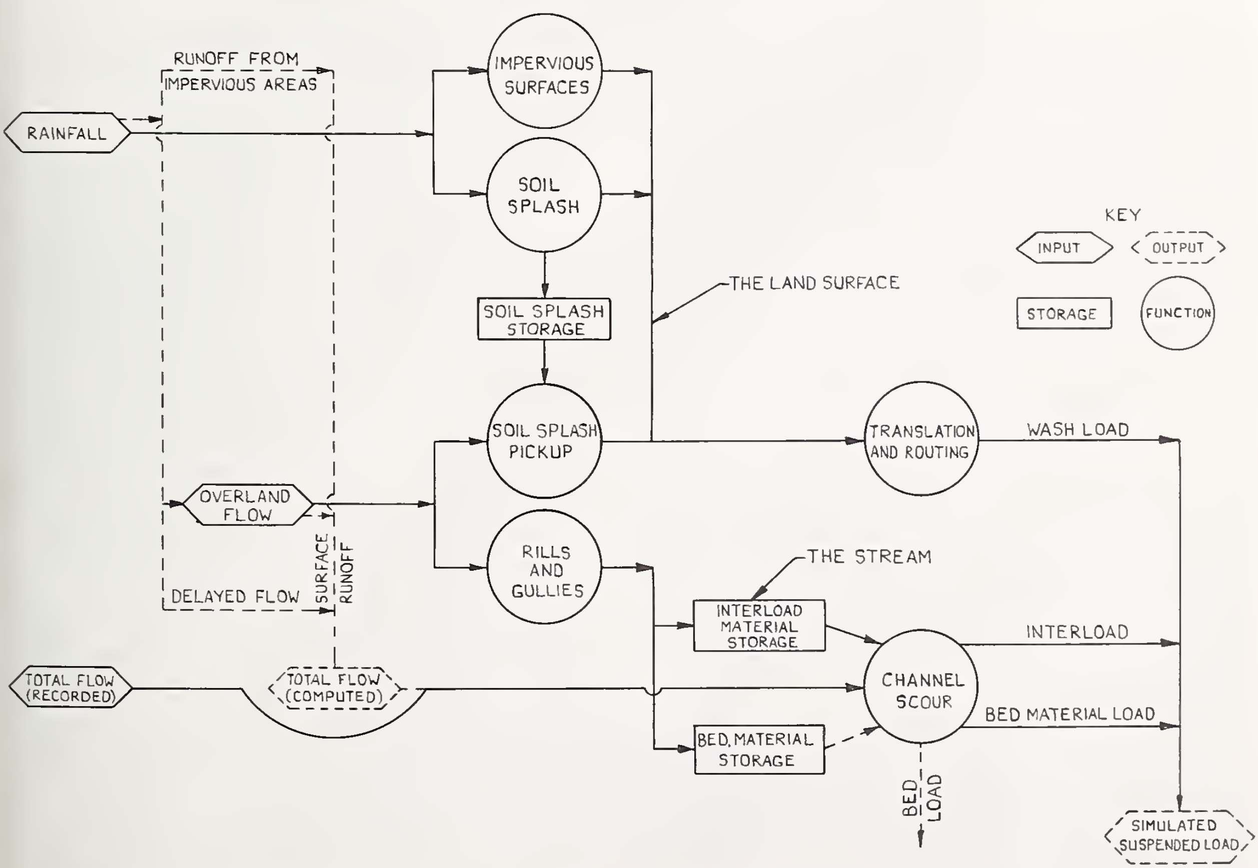

FIGURE 4.—Sediment model flow chart (after Negev, *24*).

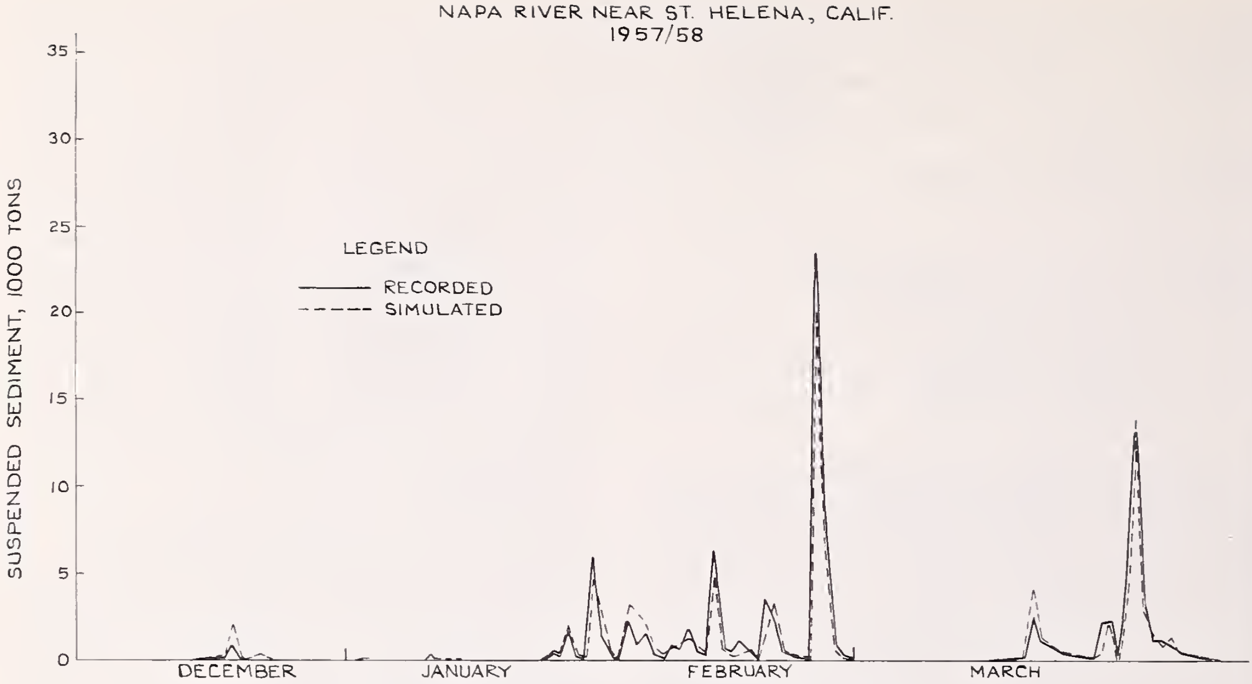

FIGURE 5.—Sediment simulation by the Negev model.

A COMPREHENSIVE SEDIMENT MODEL

The development of a comprehensive sediment model involves the initial step of outlining its basic structure showing the key processes and their interrelationship. Figure 7 represents the outline of the author's proposed structure for a complete sediment model. Like any model, this structure will be updated as more concepts are included. Sediment models of this kind must be an integral part of a model representing the hydrological processes as shown on figure 1, but structured in such a way that it can be used for different design purposes without calling on all the parts of the model. For example, if sediment yield estimates were the design problem, then only the model routines relevant to this objective need be called into use by the computer. By this way computer time and costs are reduced in the analysis of the problem. The model would consist of a set of routines each with special-purpose features, but when used together give general-purpose application.

The top half of the flow chart in figure 7 represents the combined land phase sediment and hydrology processes. To the left is the flow chart of the land surface hydrology processes of the Hydrocomp simulation program. This computes the component of land surface runoff into the stream channel network. To the right are the land surface fluvial, chemical, and mass erosion processes also contributing the stream channel network.

The land surface processes are computed for unit area of watershed for a given set of parameters representing the hydrology processes of infiltration, interflow, overland flow, soil moisture storage, ground water, etc., and the sediment processes of soil splash, rill and gully development, creep processes, etc. Since these parameters vary throughout a watershed, it is necessary to divide the watershed into subareas and specify a set of parameter levels which represent in a lumped manner the characteristics of the subarea. Subareas are usually referred to as segments, and figure 8 shows the division of a watershed into three segments representing broadly the mountainous, middle, and lower reaches of a hypothetical river. As many segment divisions may be made as accuracy requires, and depending on the purpose of the simulation, the divisions may be by soil type, elevation band, vegetation type, rainfall isohyet, etc. Output from the land phase of the model supplies computed information on the timing and magnitude of the combined land surface runoff and

sediment yield to the stream channels within the designated segment.

The next step in the model is the calculation of the movement of both water and sediment along the stream channel and any scour, storage, or diversions into or out of the system. Several methods of streamflow routing have been employed in the past, including unit hydrograph and Muskinghum techniques. Kinematic routing techniques have been found to give a better representation of the river network response, and are included in this model. To utilize the kinematic routing method the channel network of the watershed in figure 8 has been divided into a series of reaches, and the physical characteristics of channel cross-section dimensions, roughness, depth, flood-plain slope and roughness, and reach length and slope are specified for all reaches. As many reaches can be used as accuracy may again require, thus providing a physical basis for flow and sediment routing and scour and deposition calculations. Within any watershed the channel cross-section slope and roughness can vary considerably as it is shown schematically in figure 8. By representing the reaches in the above way it is possible to account for the nonlinearity of channel response and the effects of localized storms within the watershed.

In figure 8 the reach 8–9 represents a reservoir whose routing and sediment characteristics are treated differently from the channel reach. Where a river system contains one or more reservoirs, these are easily represented by the model. The processes of water/sediment inflow, releases, and spillway discharge can be made and the reservoir can be subdivided into subreaches to calculate, in more detail, the internal circulation and sedimentation rates. The combined water/sediment outflow from a reach form inflow to the next downstream reservoir or reach and

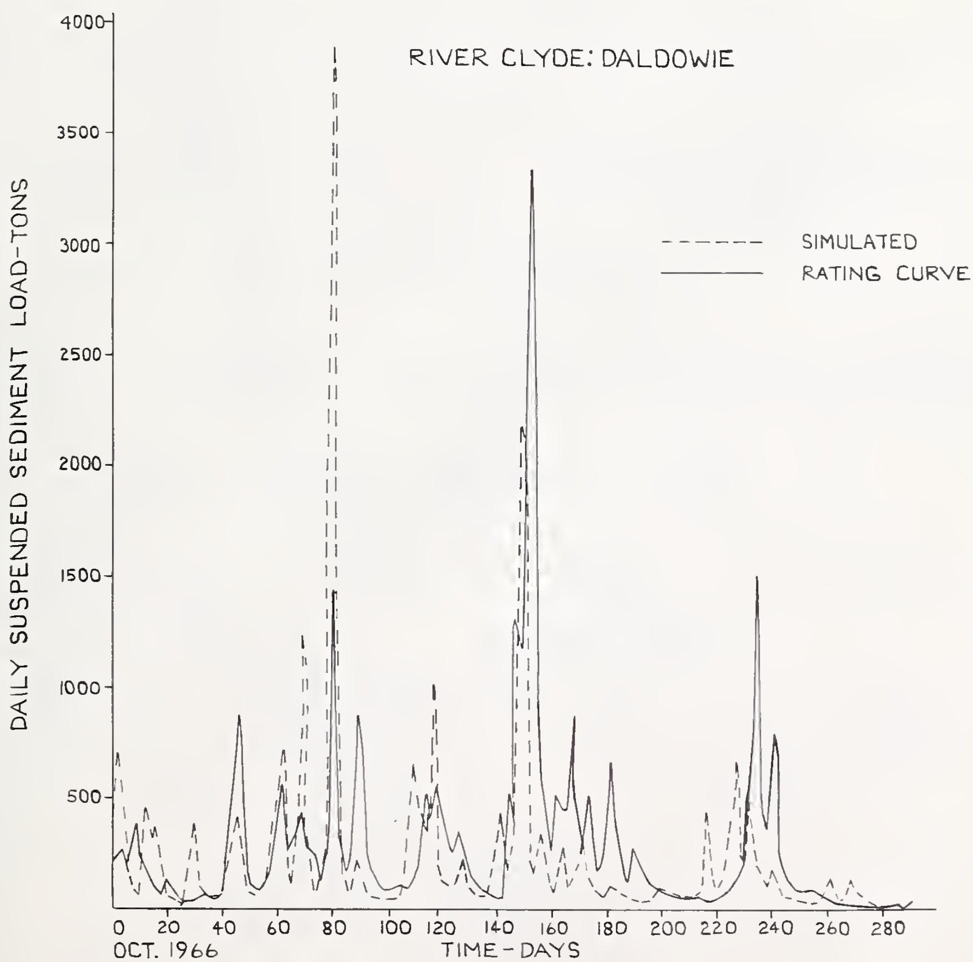

FIGURE 6.—Comparison between simulated suspended sedment and rating curve estimate.

there together with the local inflows or outflows, the routing, scour and deposition calculations are repeated until the last reach where outflow passes to the sea via an estuary.

To apply such a model to a watershed it is first necessary to calibrate the model parameters such that the model reproduces recorded data on streamflow, sediment loads, river stage, channel scour, and reservoir sedimentation. Figure 2 shows the parameter adjustment step. Techniques in model calibration are presented elsewhere (*16, 19*). With a model calibrated to repro-

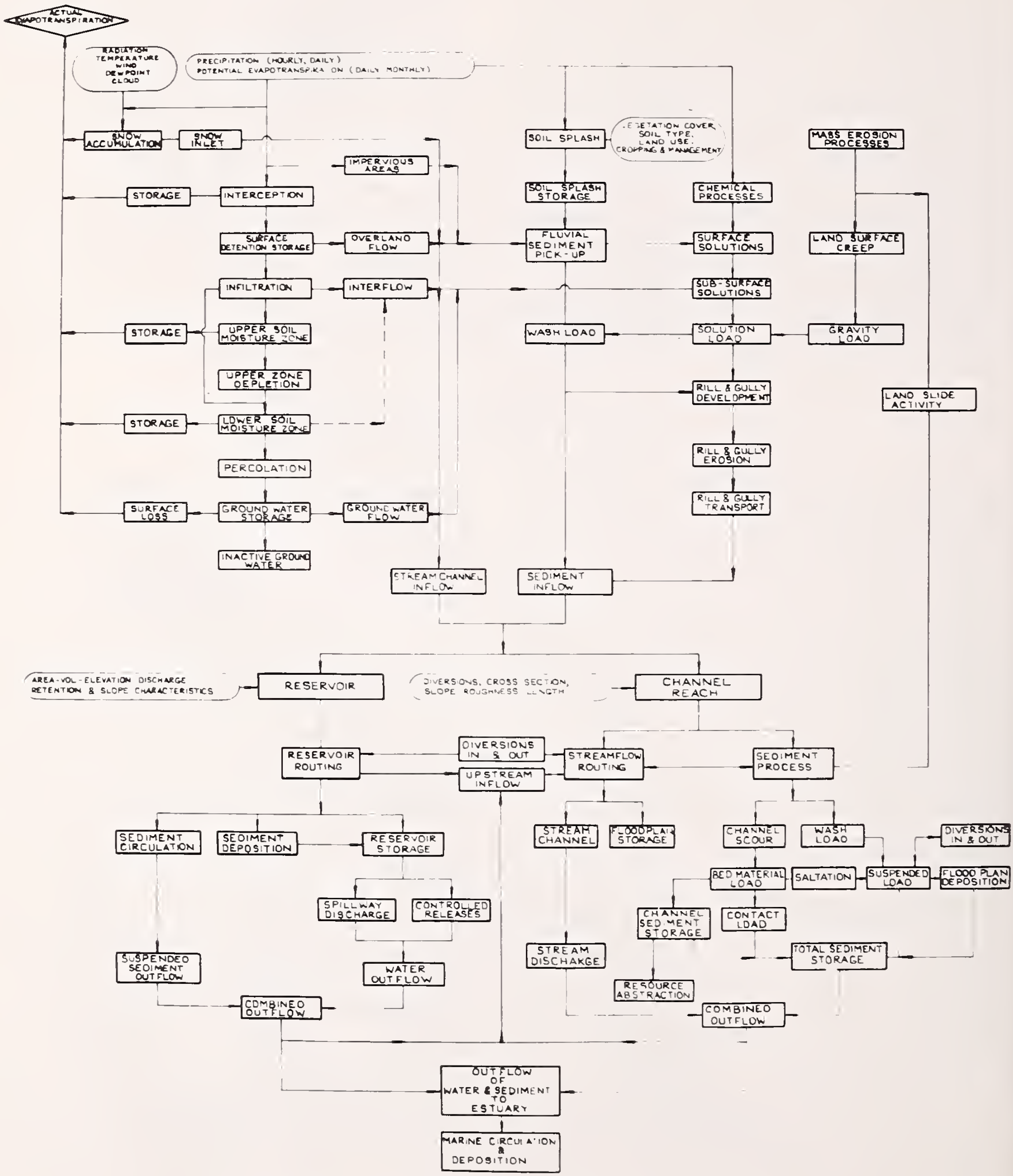

FIGURE 7.—Flow chart of a conceptual sediment simulation model.

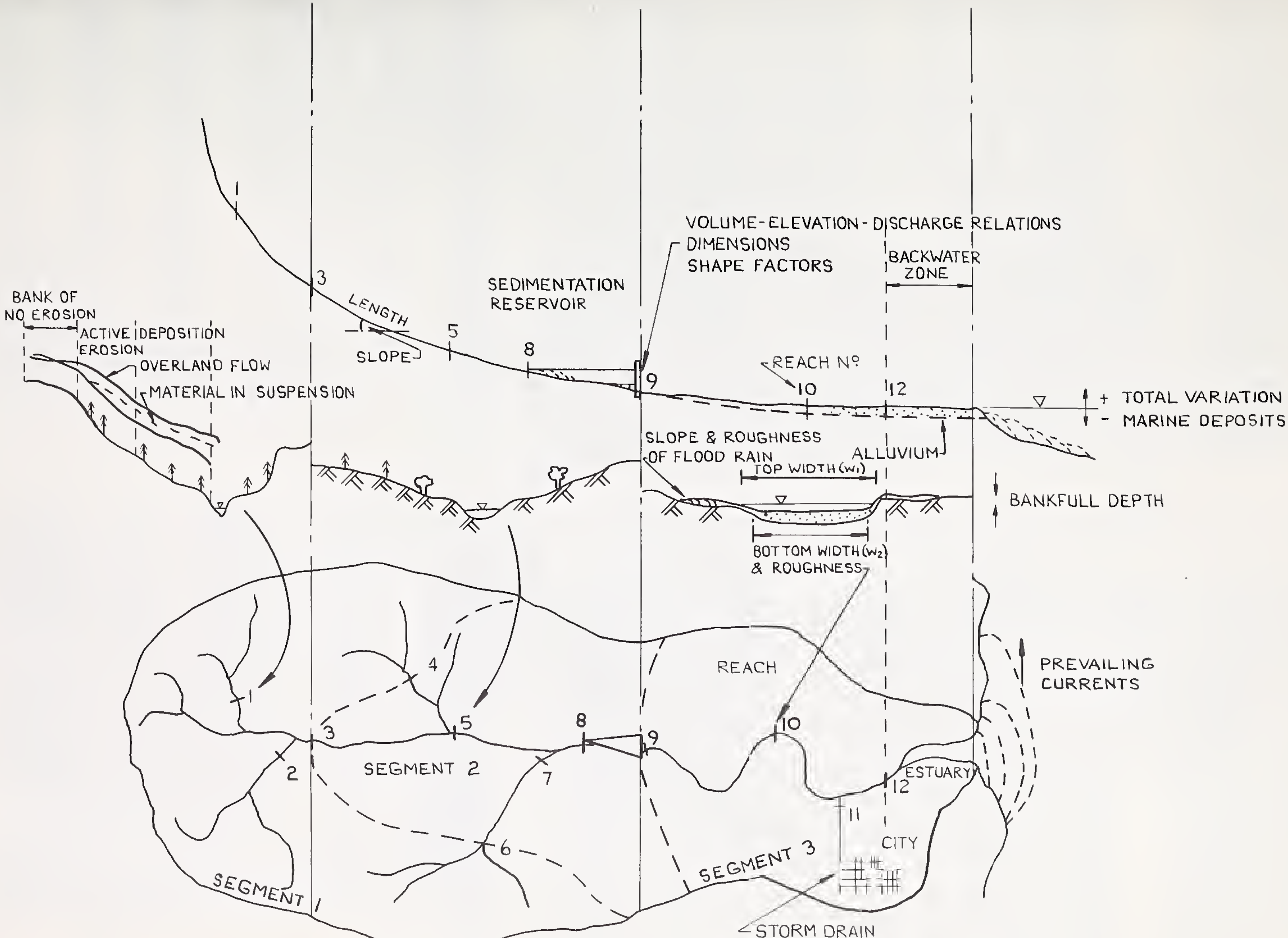

FIGURE 8.—Division of catchment for simulation.

duce recorded information, it is possible to use it to estimate the effects of changes to existing catchment characteristics, for example, the effects of vegetation management on water yield (*17*) and sediment yield and reservoir deposition; the effects of urbanization on peak flows and scour rates; and the effects of a reservoir on the sediment transport processes. A major drawback at the present stage of sediment model development is the lack of comprehensive data on both the continuous hydrology and sediment processes.

SUMMARY AND CONCLUSIONS

Computer simulation is one of several techniques in mathematical modeling. It is an attempt to represent the time variant interaction of physical processes. The use of the method in hydrological simulation has had widespread success. In sediment simulation only rudimentary steps have been taken to model this complex subject, considering the wealth of theory available today. Due to the dependency of sediment processes on the hydrology of a catchment, the trend in sediment simulation will be to extend watershed hydrology models. The same is true for water quality models.

The complex assessment problems confronting engineers and planners require an integrated approach to the analysis of the total catchment. Relatively minor changes in land use, flood control, weather modification, and urbanization can seriously affect the hydrology and sediment response of a catchment. It is not always sufficient to treat only one facet of the sediment problem. For example, sediment discharge formulas have had limited success partly due to inadequate assumptions on the sediment supply processes. Simulation techniques provide a tool by which the effects on catchment response due to changes in catchment characteristics, whether natural or manmade, can be studied with a view to better decisions in planning, management, and operation of the watershed.

The next 3 years will see an acceleration in the international development and use of simulation techniques applied to sediment processes. The limiting factor in this development will be the availability of adequate data on measured sediment erosion, transport, and deposition by which to compare and verify the models under development. The continuing need for a comprehensive data collection program remains a prerequisite for the successful development and use of a conceptual simulation model of sediment erosion-transport-deposition.

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